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*Article*

# Evidences of the Influence of Particle Size on the Incidence of Micro-Fractures in Blast-Conditioned Rock

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**Abstract:** In the mining industry the most energy/demanding activity is particle size reduction, i.e. comminution. Blasting is the first stage of comminution. It has been experimentally and by field observation demonstrated that blasting produces two effects on rock: i) it produces macroscopic fracturing, fragmentation; ii) it generates microscopic fracturing, a series of microfractures that weaken the rock, reducing the specific Work Index, therefore making it less resistant to crushing and milling. The present work is aimed to verify the following hypothesis: do smaller particles, having been macroscopically more affected by blasting, also possess a higher degree of microfractures, therefore being less resistant to grinding? To verify this hypothesis we analyzed blasted rock under three test dominions: macroscopic testing via point loading, laboratory grinding testing via Bond's mill to determine the blasted Work Index and microscopic optical observation of microfractures. The results show that macroscopic testing cannot appreciate microscopic weakening (no correlation between point load results and particle size). On the other hand, laboratory ball mill and microscopic optical observation results show a direct correlation between particle size and internal weakening of particles. The results are evidence, albeit very preliminary, that the Work Index might not be a constant within a given volume of blasted rock, and it could be a function of particle size distribution.

**Keywords:** Blasting; comminution; particle size; work index; microfractures

## Introduction

Goal n.12 of the 2030 Agenda for Sustainable Development aims to ensure sustainable consumption and production patterns [1]. In the the 2030 Agenda for Sustainable Development, there is a dedicated and stand-alone goal on energy, SDG 7, calling to "ensure access to affordable, reliable, sustainable and modern energy for all". [2].

Mining can do its part to reduce energy consumption and carbon footprint of energy generation. This paper studies this aspect from the point of view of comminution.

In the mining industry, particle size reduction (i.e. comminution) is the most energy demanding activity. It begins with blasting, and it is commonly followed by one or more stages of crushing and ore or more stages of milling (grinding). The energy consumption demand increases by order of magnitude along the comminution circuit. Figure 1 shows general figures of this increase in energy demand, while Figure 2 shows a real example of a Pb-Zn production plant: real data confirm this increase by order of magnitude both in terms of specific energy required to process the ore and in terms of energy demand of the equipment.

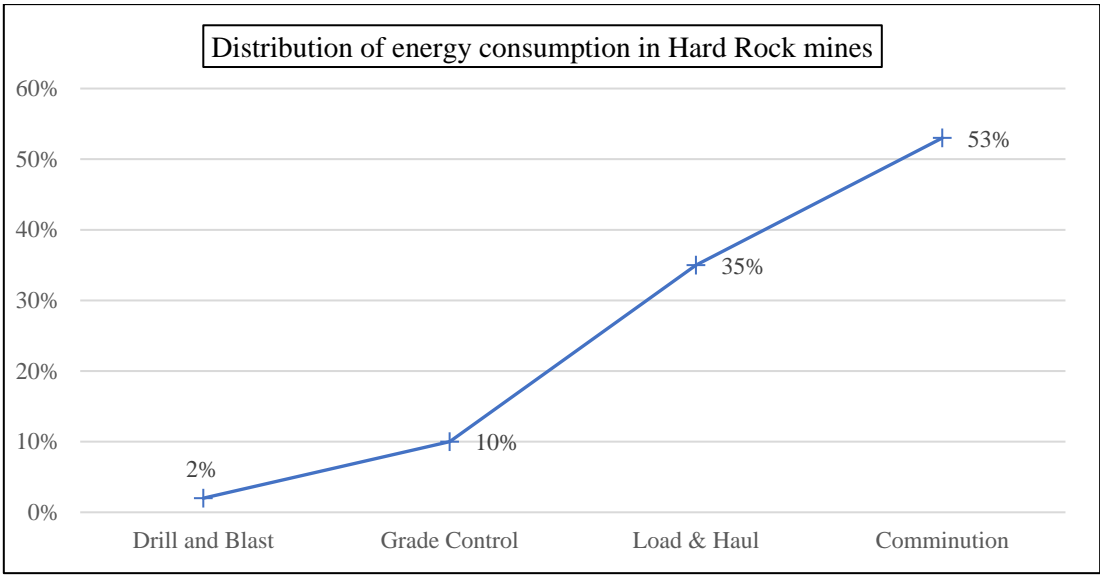


Figure 1. Progressive increase in energy demand with the finer stages of comminution. After [3].

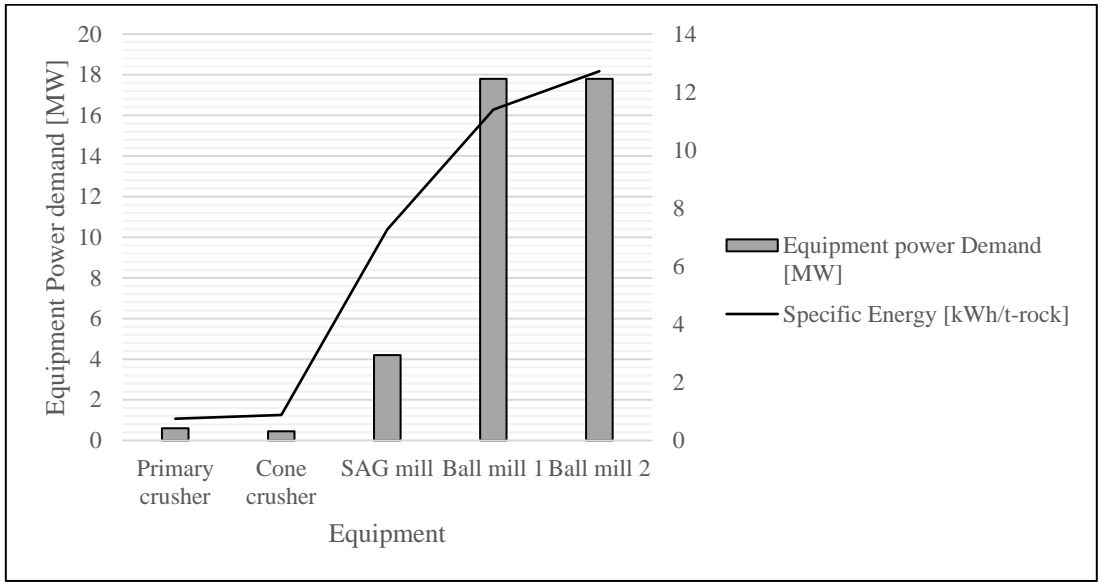


Figure 2. Data from a real case: increase in power demand and specific energy. Data from: [4].

[5] (2021) show similar figures, adding that “In the American mining industry, [...] grinding is responsible for 40% of the electricity used in the mines”. The work previously cited in Figure 1 by [3] points out the following advantages from better fragmentation of ore:

- Increase in ore recovery ratio;
- Decrease in energy waste (mainly due to increasing the temperature of the material instead of fragmenting it);
- Decrease in greenhouse emissions (comminution accounts for over 60% of the whole mining process).

Being blasting the least energy-consuming phase, great advantage can be taken from this activity to benefit the downstream processes and reduce the energy demand of the mining operation. Table 1 summarizes the meaning of such benefits.

As per the macroscopic rock fragmentation and its effects on downstream operations, literature is abundant and with many insights (see just as some examples: [6–15]). Over the years several prediction models of the particle size distribution of the blasted muck pile that obtain good fitting with sieving. To mention some, the KUZ-RAM [16,17], the SWEBREC [18] among other studies [19]. In more recent year, the concept of the Fragmentation-Energy fan saw light [20]. it considers the

percentiles of the particle size distribution (fragmentation) vis-a-vis the specific charges (energy in a log-log graph: they fit well in a fan fashion where straight lines tend to converge to a focal point (fan).

Table 1. Benefits for comminution offered by blasting.

What Comminution Needs	What Blasting Offers
Small particle size	A particle size distribution adjustable to a desired range varying drill&blast parameters
Low internal resistance of the grains	A system of micro-fractures, invisible at the naked eye, that somehow "softens" the material reducing the internal resistance

The microscopic weakening of the grinding resistance by means of micro-fractures (microscopic) has a different impact in scientific literature. Studies are not so common. [21] pioneered the research: by means of microscopic analysis and laboratory tests they showed that increasing the Powder Factor (P.F). achieves significant reductions in Bond Work Index [22] due to the presence of micro-fractures in the material. [23,24] report and discuss a wide selection of them.

Figure 1 shows a general trend line obtained from results of experimental blasts at small-scale. Table 2 shows the results at industrial scale how increasing blasting at the mine benefits comminution circuits at the plant.

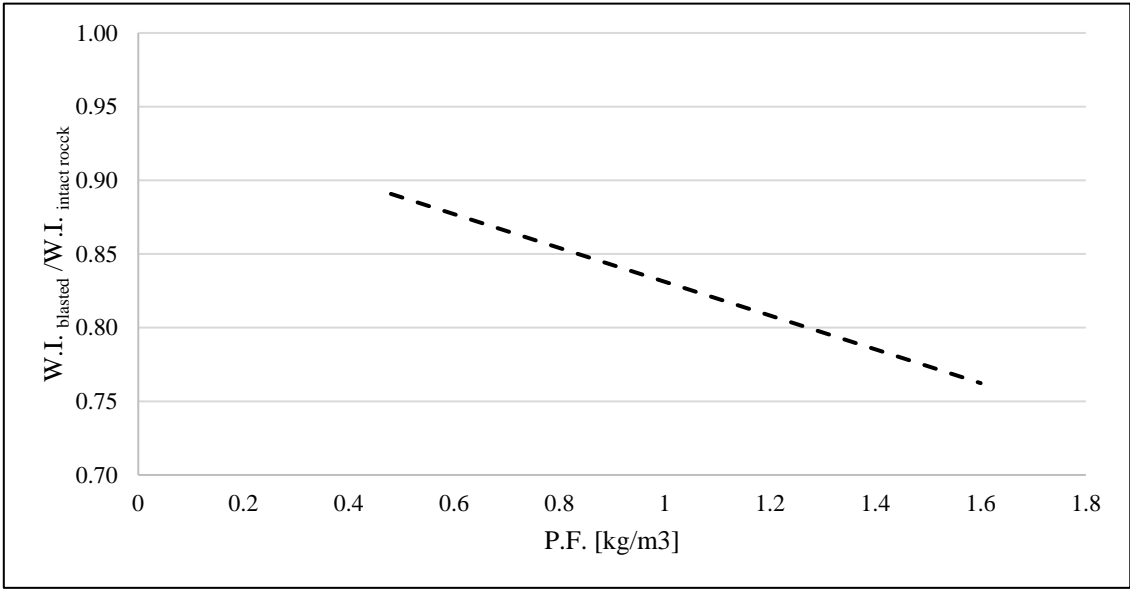


Figure 3. Reduction of the W.I. of blasted rock at the increase of the specific explosive charge. At laboratory scale. (Analysis of data by [21,25,26]).

Table 2. Selected studies showing the effects on comminution at the increase of blasting energy. After [23,24].

Blasting changes	Effects in comminution	Material
P.F. + 240%, Specific Priming (Delays/t) + 400%	Stops at the primary crusher -79%, Electricity Consumption at primary crusher - 27% , Total Production Costs -34%	Marble
P.F. + 40% (D&B costs +40%)	Mill throughput + 16%, Grinding costs - 19%	Gold ore
P.F. + 42%	Excavator productivity + 14% Crusher throughput + 30% Grinding throughput + 10%	n.a.

P.F. +25%	Mill Energy -10%	Metal ore
P.F. + 33%	Comminution Energy at SAG mill -29%, total Greenhouse emissions -20%	Gold ore
P.F. + 65%	SAG mill throughput + 14%	Gold ore

The present work is aimed to study the relationship between the size of blasted fragments and their resistance. In particular, to verify the following hypothesis:  
*do smaller particles, having been macroscopically more affected by blasting, also possess a higher degree of microfractures, therefore being less resistant to grinding?*

Materials and Methods

The rock for the present study is a copper-bearing andesitic lava, 1- 4% Cu. It has a porphyritic texture, with plagioclase phenocrystals of 1-10 mm and epidote and amphiboles alterations of 1-3 mm. The samples come from production blasts at the Experimental and School Mine of the the Universidad Catolica del Norte: a small-scale mining operation in the proximity of Antofagasta, in the II Region of Northern Chile. The specific blasts origin of the fragments studied here were a series of unconventional ones to widen the tunnel, therefore it is not possible to determine a specific explosive charge (P.F., kg/m³). Details of the characterization of this rock are given in the following sections of this document.

For the evaluation of the influence of particle size on the weakening of rock they were used the tests of Table 3, where the reason and the standards employed are detailed.

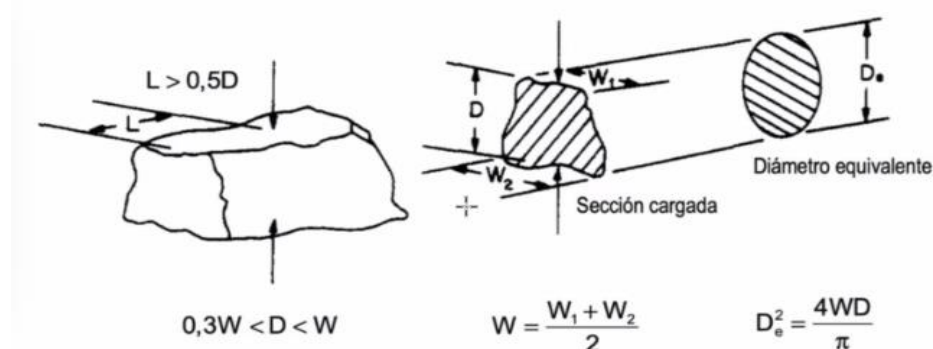
Table 3. Tests used during this study.

Test	Reason	Method
Point Load test	Evaluating the effect of microfractures at the macroscopic scale	Standard Point-Load tester (ISRM 2007)
Bond’s Work Index test via ball mill	Evaluating the reduction of resistance to grinding of the rock due to effect of the microfractures	Standard Ball Mill test (after Bond 1952)
Microscopic measurement of fractures	Optical observation	Microscopic observation of blasted mineral sealed in briquettes for fitting under the microscope lens (National Research Council, 1996)

Point Load Tests

Point Load Strength Test

The point load strength test is used to estimate the  $\sigma_c$  of rocks without having to prepare perfectly machined cylindrical samples. Irregular fragments have been used to perform this test and the indications of [27] have been followed. The geometric conditions that this test must meet for each fragment are that the cross-sectional area is greater than 500 mm², the relationship between the distance D and the width of the cross section W is between 0.3 and 1 ( $0.3 < D/W < 1$ ) and that the distance from the point of application of the load to the free face in a direction perpendicular to the cross section is greater than half of D ( $L > 0.5 D$ ), as shown in Figure 3.



**Figure 3.** Condiciones geométricas de los fragmentos de roca para el ensayo de fragmentos irregulares (ISMR, 2007).

The procedure for estimating  $\sigma_c$  consists of calculating the corrected point load index,  $I_s$  (50) (Equation 1) and multiplying it by a factor  $F$  that varies between 0 and 1 (Equation 2). To determine the value of the factor  $F$ , the Brook size correction (1985) was used using equations 3 and 4.

$$I_{s(50)} = 10^3 \cdot \frac{P}{D_e^2} \quad 1$$

$$\sigma_c = 22,6 \cdot F \cdot I_{s(50)} \quad \text{where } 0 \leq F \leq 2 \quad 2$$

$$T_{500} = 211,5 \cdot \frac{P}{A^{0,75}} \quad 3$$

$$3\sigma_c = 12,5 \cdot T_{500} \quad 4$$

where  $I_{s(50)}$  is the corrected point load index (MPa),  $P$  is the breaking load (kN),  $D_e$  the equivalent diameter of the fragment (mm),  $T_{500}$  is the point load index (MPa),  $A$  the area of the loaded section (mm<sup>2</sup>) and  $L$  the distance between the contact points and the free face in a direction perpendicular to the cross section (mm).

### Samples for Point Load Tests

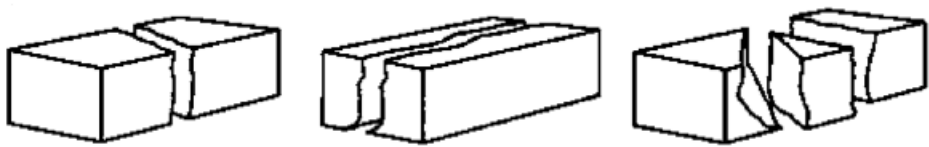
To begin with, rock fragments were collected from the debris produced by two different blasts carried out inside the site. These fragments were prepared so that they had flat faces. For this, the Controls Group cutting saw was used, thus providing a better contact surface at the loading points. In addition, the size of the fragment was regulated so that it could be tested. The samples were classified according to the blast with the following nomenclature:

- First blast (T1)
- Second blast (T2)

A total of thirty-one samples were obtained for the first blast (T1) and thirty samples for the second blast (T2).

To obtain the load that the fragments can withstand, it was used a Franklin press (Digital Rock Strength Index Apparatus from the Controls Group brand). The sample must be placed with high precision between the two conical tips to ensure that the load is applied in the center. The conical tips exert pressure by pumping from the hydraulic jack. This equipment has sensors that record oil pressure. The results obtained can be viewed on a real-time digital screen, which are stored for later analysis. The pressure is applied until the sample fractures and the digital screen stops the test, triggering an alarm indicating that the breaking force has been found. To validate the test, the breaking conditions of the samples were observed. Those samples that break in one or two breaking planes were considered valid, as shown in Figure 4.



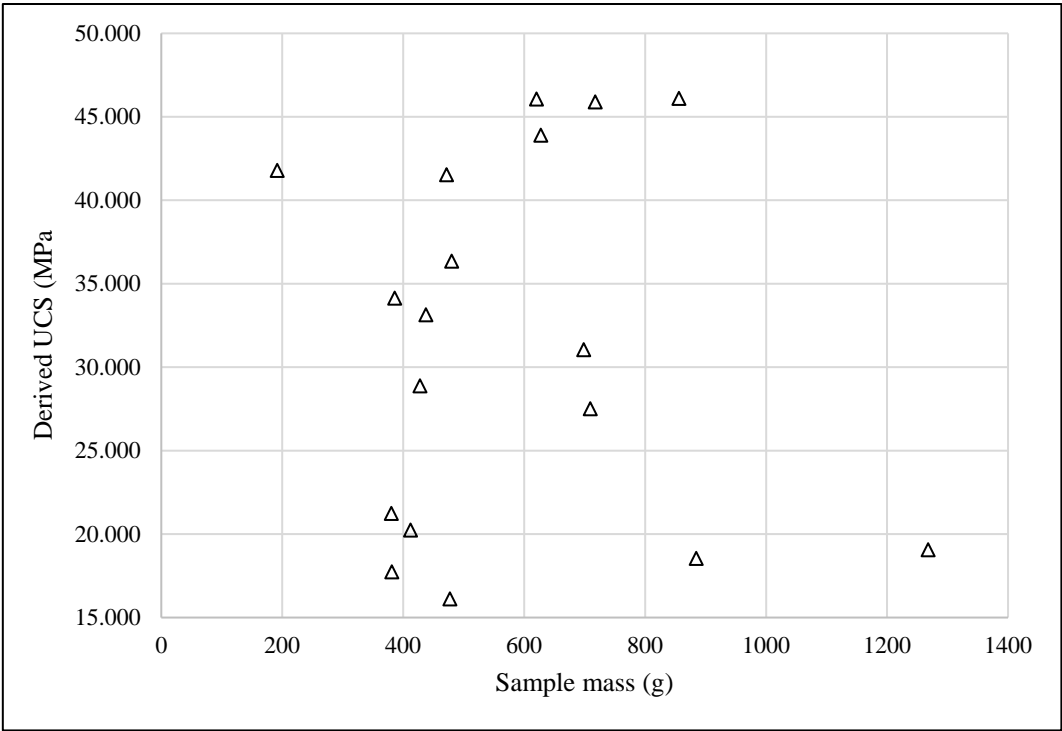


**Figure 4.** Block failure models that are considered valid after Point-Loading (ISMR, 2007).

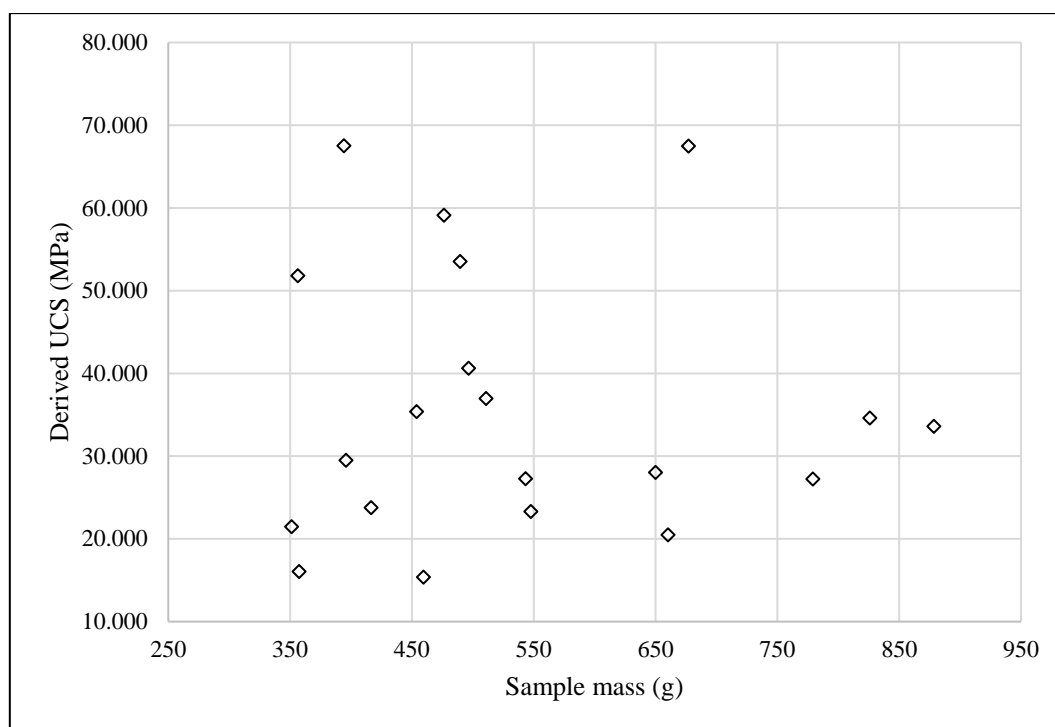
Both regular-shaped samples and irregular ones of different sizes were used.

Results of Point Load Tests

Figures 5 and 6 show the graphs of resistance to simple compression Vs. respect to the mass of the samples for blast 1 and blast 2. It is evident the lack of correlation.



**Figure 5.** UCS (derived from Point-load) vs size (mass) of the fragment for Blast 1: there is no correlation.



**Figure 6.** UCS (derived from Point-load) vs size (mass) of the fragment for Blast 2: there is no correlation.

#### Work Index Tests

##### Work Index of Material, Work Index (Wi)

This is the value calculated in kWh/t required to reduce a material of infinite particle size by 80% passing 100 microns, which is approximately equivalent to 65% passing 200 mesh. This index establishes the relative resistance to reduction of a material within the range of sizes tested, as well as the relative mechanical efficiencies of different machines and processes. It can be determined from any commercial or laboratory operation where the applied work and the size distribution of the feed material and the product are known (Bond F. C, 1952). The following equation is used for its calculation:

$$Wi = \frac{44.5}{(Pi)^{0.23} * Gbp^{0.82} * \left( \frac{10}{P80} - \frac{10}{F80} \right)} \quad (1)$$

Pi: Sieve mesh through which 100% of the product's weight passes

P80: Sieve mesh through which 80% of the product's weight passes

F80: Sieve mesh through which 80% of the product's weight passes

Gbp: Grindability index in g/revolutions for the considered cut-off mesh

##### Specific Energy Consumption, W

This is the work or energy applied, expressed in kW-h per short ton, to a machine that reduces material from a defined feed size to a defined product size [22]. Its calculation is as follows:

$$W = Wi * 10 * \left( \frac{1}{P80} - \frac{1}{F80} \right) \left( \frac{Kwh}{TonC} \right) \quad (2)$$

Wi: SPCific Work Index of the material being grinded.

P80: Sieve mesh through which 80% of the product's weight passes

F80: Sieve mesh through which 80% of the product's weight passes

##### Material and mMethods for W.I.

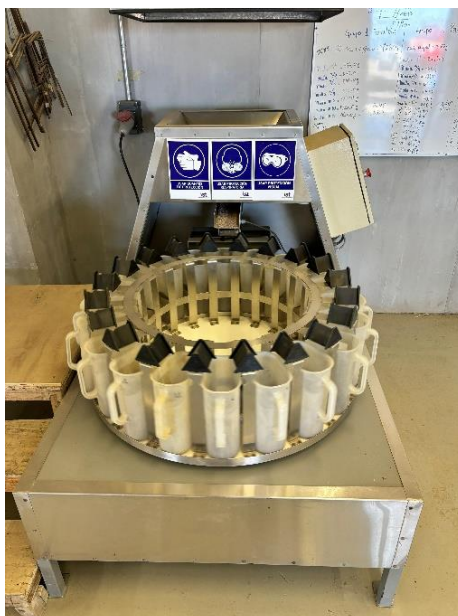
The rock fragments collected for this part of the study come from a single blast. Fragments were classified into four groups according to size:

- Group 1 and 2: quartered from a particle size fraction 5cm<D<20cm



- Group 3 and 4: quartered from a particle size fraction  $20\text{cm} < D < 25\text{cm}$

Each of the group of fragments corresponded to an amount of about 10 kg of material, considered representative. Then, all the groups were crushed separately, to obtain a particle size of the fragments finer than 6#. The 10 kg of each sample were homogenized and quartered into 20 sub-samples through a rotary sampler, as can be seen in Figure 7.



**Figure 7.** Rotary Sampler.

Then, one of the sub-samples is subjected to a granulometric analysis with a series of Tyler mesh sieves. This analysis is performed with the following mesh sizes: 8#, 14#, 20#, 30#, 40#, 50#, 70#, 100#, 140#, 200#, 325#, -325#.

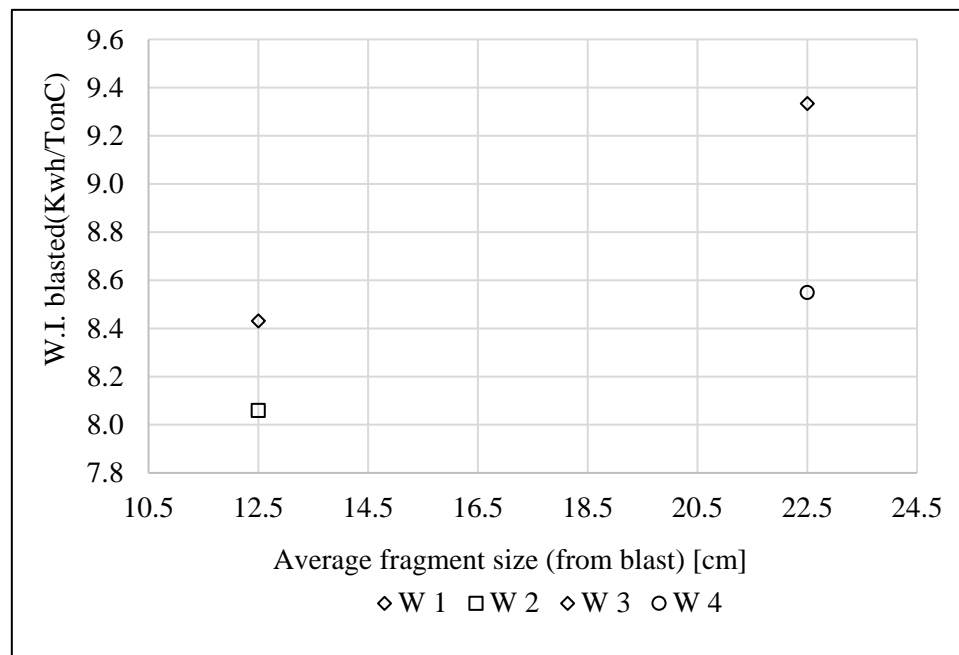
To obtain the work index values, tests must be carried out in the bond mill (Figure 8).



**Figure 8.** Laboratory Bond's ball mil.

An average of fragments size is considered for each group to generate the correlation shown in the graph of Figure 9. For groups one and two, a value of 12.5 cm was averaged, since the sizes of

their fragments range from 5 to 20 cm, for groups three and four, a value of 22.5 cm was averaged, since the sizes range from 20 to 25 cm.



**Figure 9.** Correlation between fragment size (from blast) Vs. the W.I.: the work index increases with the increase of particle size.

It appears to be a correlation between the average size of the fragments and the specific energy consumption, since the larger the fragments, the greater the amount of energy needed to reduce their size.

### Microscope Analysis

#### a) Fracture Density

Fracture density is the number of fractures in a given area. For practical cases:

$$\frac{\text{Number of fractures}}{\text{Selected area}} \left[ \frac{\text{Fractures}}{\mu\text{m}^2} \right] \quad (1)$$

#### b) Diameter of the visual field of the Microscope

The actual diameter of the observed surface is calculated by dividing the diameter of the field of view by the magnification of the objective and eventually by the tube factor, where the formula is:

$$D_{FV} = \frac{FN}{M_O * M_T} \quad (\mu\text{m}) \quad (2)$$

$D_{FV}$ : Diameter of the visual field in the plane of the specimen.

$FN$ : Field number in millimeters.

$M_O$ : Objective lens zoom.

$M_T$ : Tube lens magnification factor.

#### c) Samples

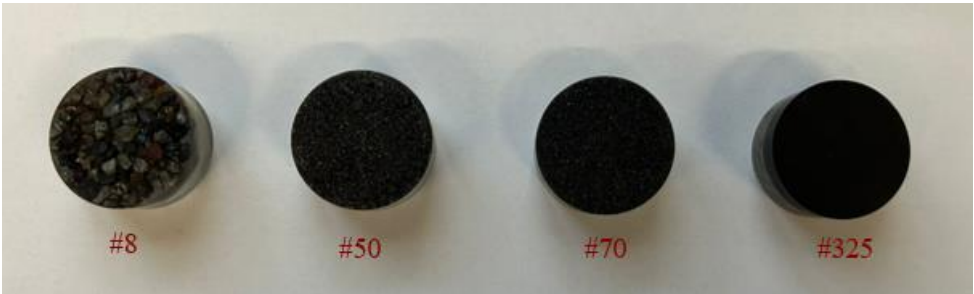
The samples come from the same blast of the previous experiments. Approximately five kilograms of samples were collected, then sieved, starting # 4 to # 325.

Once the samples have been separated by size, four mesh sizes are selected (Figure 10).



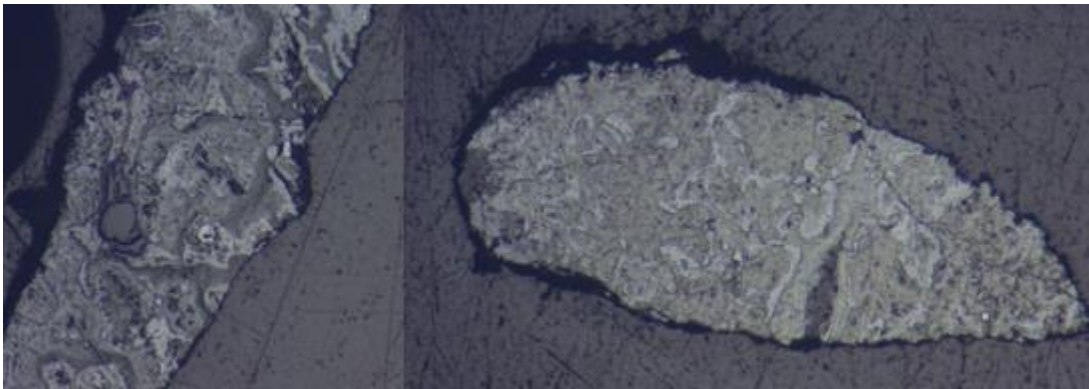
**Figure 10.** Selected simples: particles ), which are retained at #8, #50, #70 and #325..

In order to carry out a correct observation under the microscope, the selected samples must be placed in polished briquettes. In this case, the MAINI® scientific team helped to create four polished briquettes reassociated with each selection mesh..



**Figure 11.** Polished briquettes for each sample.

The polished briquettes are placed in a MCS-IM100 Microscope, obtaining images like the one of Figure 12. Between 4 and 5 images are necessary for each zoom and for each mesh sample to be representative, for a total of 26 pictures taken.



**Figure 12.** Microscopic visión of a blasted sample.

Once the images required for the study have been obtained, the diameter of the visual field is calculated according to Equation 2, giving the results as diameters expressed in Table 4. Figure 13 shows an example of a visual diameter with scale.

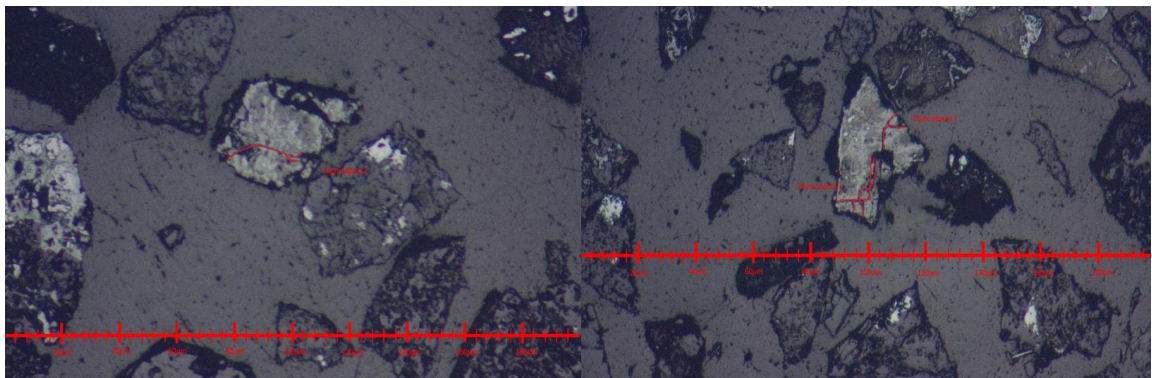
**Table 4.** Diameter of the visual fields used for the study.

<i>Lens Zoom</i>	Diameter of the visual field (µm)
4x	500
10x	200
20x	100



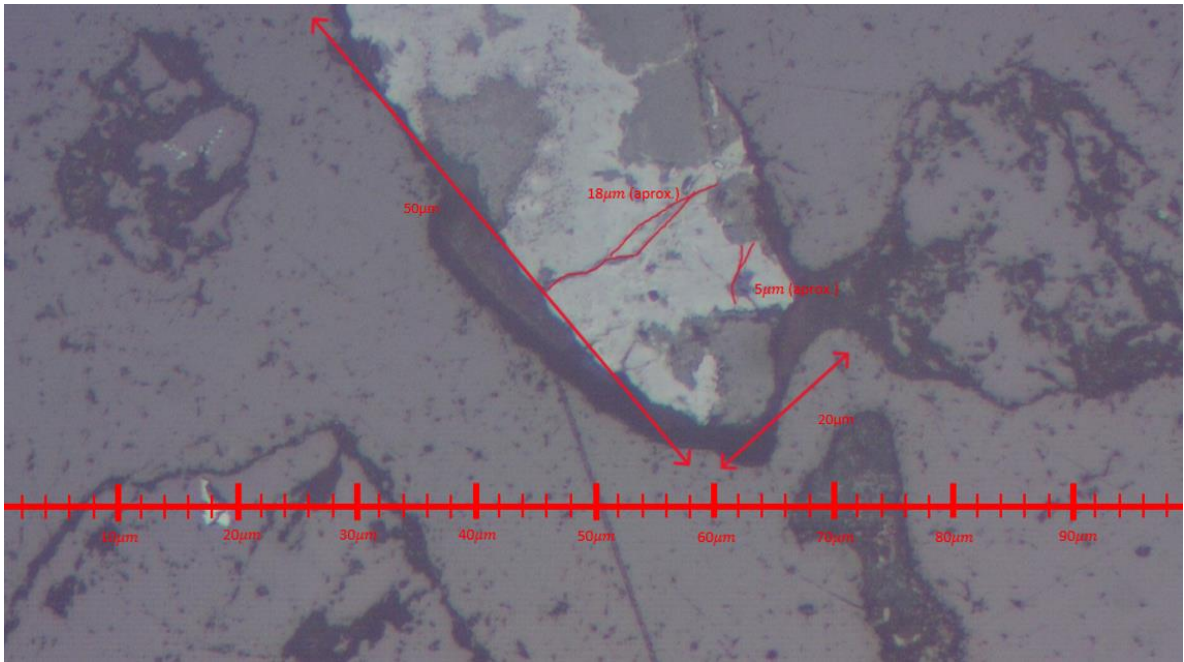
40x

50



**Figure 13.** Visual representation of the diameters obtained.

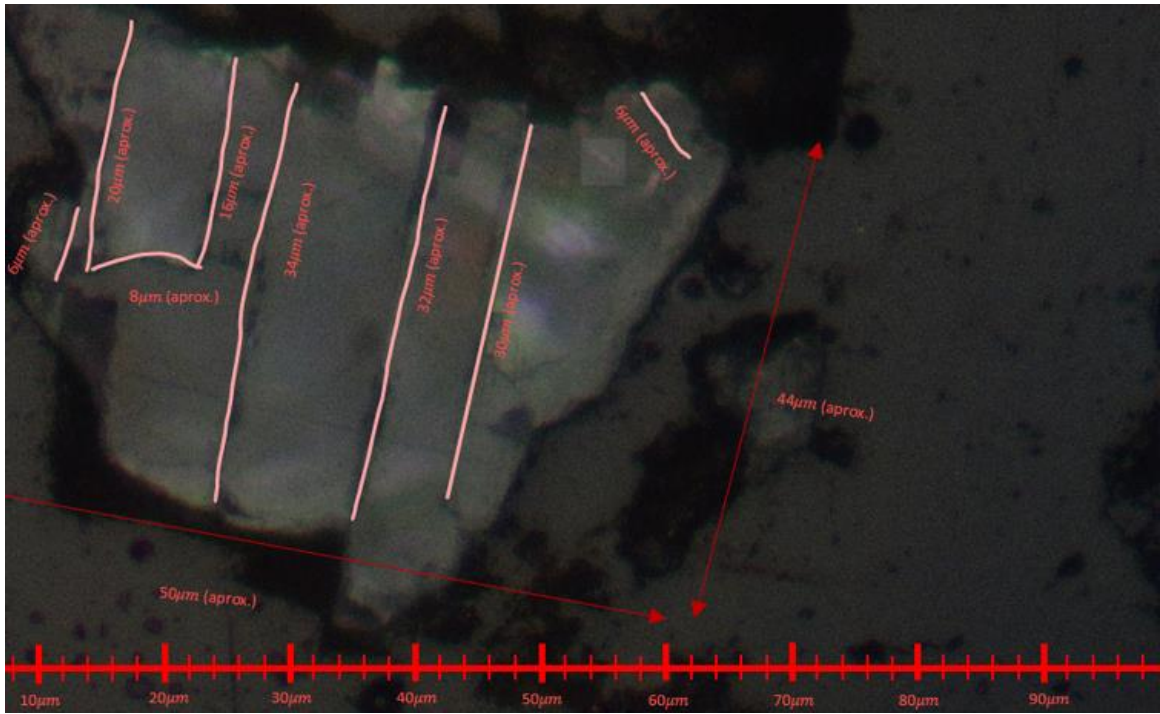
Subsequently, it is determined the area of the mineral particles observed in the images. The area corresponds to the maximum width by the length of particle in the sample: this is a way of standardizing the calculation of the area for all the samples.



**Figure 14.** Representation of the calculation of the area of each sample.

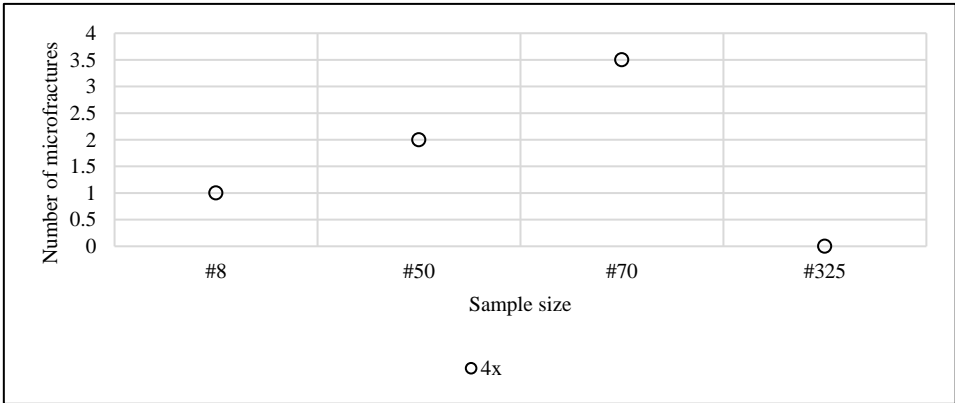
*Results from Microscope Analysis*

Figure 15 show a typical result observed: the presence of a net of induced discontinuities (microfractures), which are not typical of the mineral. This was the case for all sample sizes.

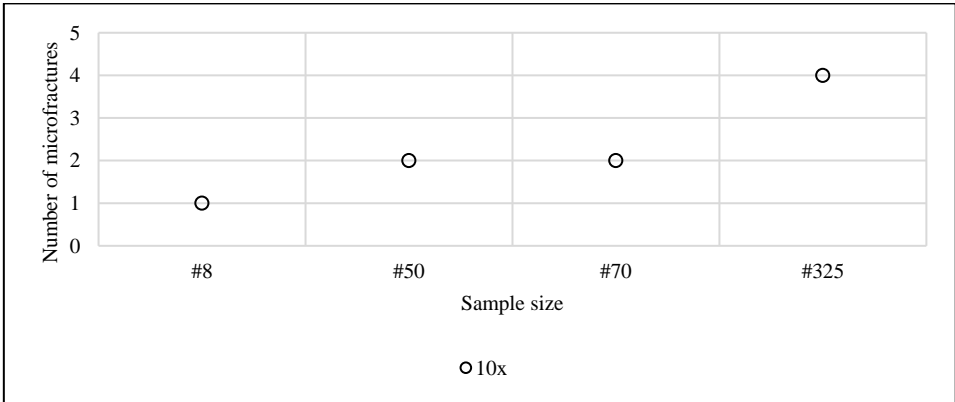


**Figure 15.** The visible net of microfracture induced by the explosive.

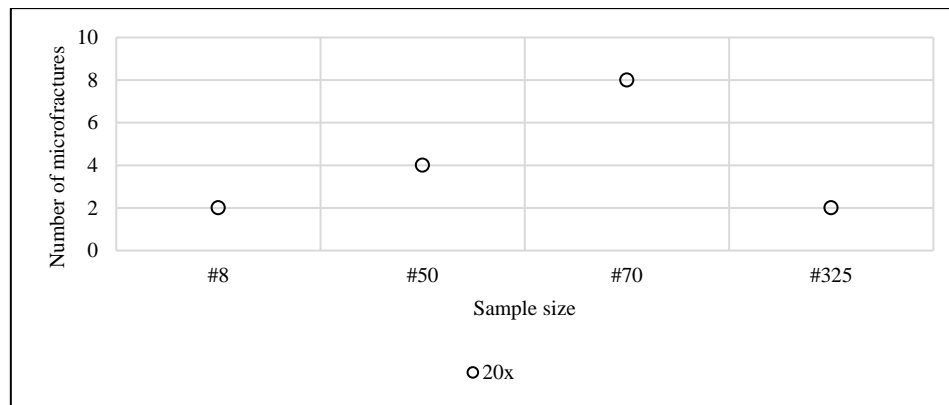
Figures 16–19 show the correlation sample size vs. number of fractures for each microscope lens zoom.



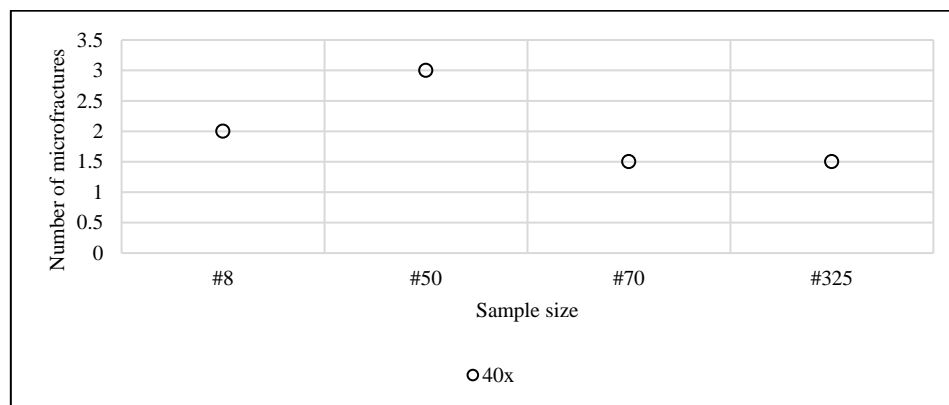
**Figure 16.** Number of fractures vs sample size for a 4x lens zoom.



**Figure 17.** Number of fractures vs sample size for a 10x lens zoom.



**Figure 18.** Number of fractures vs sample size for a 20x lens zoom.



**Figure 19.** Number of fractures vs sample size for a 40x lens zoom.

It appears to exist a correlation between particle size and the density of microfractures. The tendency is visible until the 20x zoom. The most evident is at the 10x zoom. In the largest zoom increment, one loses the perception of special distribution of fractures. Further studies will analyze more samples to address the influence of the zoom-size of visual field effect on the measurements.

## Discussions

The results obtained give some insights regarding how to investigate macroscopic and microscopic effect of size-dependant pre-conditioning of rock via blasting. Our macroscopical approach was using the Point Load Test (PLT) as a mean to investigate the influence of particle size in the weakening of the blasted rock. The results gave no correlation between PLT strength and particle size. This indicate that, at least via PLT, one cannot appreciate this size-depending weakening at the macroscopic scale. This helps to rule out a type of test when investigating this topic For microscopic effect we used the Bond's test for calculating the Work Index and microscopic observation to measure the length of blast-induced fractures in the blasted rock. The results from both tests gave the same results: microscoping weakening of the blasted material is size-dependant. First of all, this confirms that these two tests are effective to measure the microscopic size-dependency of the pre-conditioning of rock by the explosive.

As for the meaning of the results obtaines, the size-dependency of the grade of blast-induced weakening of rock, one must note that these results are very preliminary as they are based on a limited amount of tests. The interpretation suggests that the  $W.I._{blasted}$  is not a constant in a given volume of blasted rock.

This of course must be discussed considering other variables, such as lithology. For example, [25] from small-scale blast tests in granite and consequent measurement of  $W.I._{blasted}$  in ball mill, observed that the explosive decreases at smaller particle sizes, and that it is improbable to induce micro-fracturing at a scale smaller than the one of the mineral grains of the rock. Their that the effects

of micro-cracking depend on the lithotype. The fractures observed in the present study break transversally the grains of the rock, mainly the plagioclase phenocrystals.

The authors of this study will continue this research with more material coming from more blasts at the same mine. The next stages of the research will include a proper measurement of the Powder Factor of the blasts.

## Conclusions

In the introduction it was explicated the Research Question of this study:

*do smaller particles, having been macroscopically more affected by blasting, also possess a higher degree of microfractures, therefore being less resistant to grinding?*

This research analyzed blasted rock under three test dominions:

- macroscopic testing via point loading,
- microscopic mechanical testing via Bond's mill
- microscopic optical observation of microfractures.

Macroscopic testing seems to be unable to appreciate microscopic size-dependency weakening of blasted rock.

Microscopic mechanical and optical results, on the other hand, show a direct correlation between particle size and internal weakening of particles. The results are evidence, albeit very preliminary, that the Work Index might not be a constant within a given volume of blasted rock, and it could be a function of particle size distribution.

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