Fragmentation Efficiency of Comminution under High Velocity Impact

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Abstract

For several decades, the mining and mineral processing industry has contended with high energy costs of which a large portion is due to mineral comminution operations. This is related to the low fragmentation efficiency of comminution which ranges from a value of only ~1 percent to a few percent and is typically accompanied by low impact velocities ranging from 1 to 10 $m{\cdot}s^{-1}$.

In order to study comminution at higher strain rates than those of conventional equipment, a compressed-air gas gun apparatus has been developed to directly measure the quantitative parameters of impact velocity on aggregated rock samples. Experiments have been conducted on three materials at projectile velocities up to 450 $m{\cdot}s^{-1}$.

The results suggest the energy efficiency of rock breakage can be improved by as much as 2 to 3 times under high velocity impact for the same energy input level. Data analysis and trends are influenced by the impact zone dimension, the hardness and porosity of the material, and the degree of constraint of the sample.

Keywords: Comminution; Energy efficiency; Impact velocity

1. Introduction

Industrial comminution is the reduction of large particles of rocks and minerals to smaller particles and fragments via compressive loading operations such as crushing and grinding. Estimations of energy consumption by DOE [1] indicate that comminution consumes approximately ~29% of the total mining industry energy in the USA; a number that is likely to be applicable to worldwide mining operations and useful for assessing the national energy consumption in different mining countries. In this manner, comminution is estimated to consume between 0.39% and 1.86% of the total national energy consumption of countries with significant mining operations, the lower number being applicable to the most highly industrialised nations where mining forms a lower fraction of the total industrial sector [2].

In addition to the high operating costs, comminution is also highly inefficient based on the mechanical energy input required to create the new surface area (energy) [3]. Using this definition, the fragmentation efficiency has been shown to be of the order of 1–2% [4,5]. Typical grinding efficiencies range from 1% to 2%, a problem compounded by the fact that grinding consumes the majority of the total energy used during mineral recovery, and crushing efficiencies are slightly higher at 3–4%. However, blasting efficiencies are several times higher than comminution [6].

Traditionally, ball mills and rod mills have been used in comminution circuits in which the values of the loading forces in these machines have a wide distribution, leading to inefficient fracture. The impact efficiency of particle fracture depends on the loading force, the size and orientation of inherent flaws and other fracture mechanics features. In addition, inefficiency is the result of numerous impacts before one sufficient force causes particle fracture [7]. Many impacts may be required to achieve particle fracture depending on the loading force, the cyclic nature of loading, and the orientation of particles between consecutive impacts. Unsuccessful impacts generate elastic strain energy in the particle which is released as thermal energy without producing any new surface area, thus contributing to the overall inefficiency of the comminution process [8]. The major mechanisms of breakage in comminution occur by either attrition or impact loading generated by gravity in a static regime at low impact velocity ranging from 1 to 10 $m \cdot s^{-1}$.

It is generally recognized that strength characteristics of materials under static and dynamic loading are considerably different and that the fracture stress of rocks, minerals and other brittle solids increases with increasing strain (loading) rate [9-11]. It is often considered that strain rate effects are due to crack propagation behaviour [12] such that at low stressing velocities only the largest or critical flaw is responsible for failure. However, at high loading velocities, several flaws must propagate simultaneously, due to the inability of a single flaw that has a bounded growth velocity to relieve the increasing tensile stresses. The range of typical static and dynamic loading can be shown in Fig. 1. It is evident that conventional comminution processes, which exhibit low energy efficiency, are associated with low (static) strain rates whereas blasting operations, which exhibit a higher energy efficiency, are associated with high (dynamic) strain rates or high impact velocities.

Fig. 1 Typical static and dynamic loading

	Velocity Range ($m.s^{-1}$)	**Strain Rate (s^{-1})**	**Energy Efficiency (%)**	
blasting	5,000 - 20,000	100 - 20,000	15-20	*dynamic*
this study	10 - 10^3	1 - 10^2	*?*	
conventional comminution	10^{-4} - 1	10^{-5} - 10^{-1}	1-2	*static*

In blasting, sudden increases in pressure and the rapid deposition of energy in a few milliseconds cause the rock to fracture in a dynamic environment. The explosive impact produces shock waves that move throughout the rock with high velocities [13], while in mechanical equipment, the impact occurs at low strain rates in a static regime. Few studies have been done in the intermediate strain rate range between the extreme static and dynamic loading conditions. Consequently, any attempt to study the breakage function at impact velocities higher than those of comminution equipment and lower than those of blasting would clarify the energy efficiency behaviour of brittle material in this range.

2. Rock breakage behaviour

It is well recognized that the mechanical properties of brittle materials such as rock strongly depend on the deformation rate and strain rate [14]. Experimental results show that the dynamic fracture toughness of the rock as well as crack branching is increased with increasing loading rate [15]. The results of studies performed by Sadrai et al [16] indicate that surface roughness and hence, specific surface area increases with increasing loading rate. These studies demonstrate that the rate of energy efficiency is significantly improved as loading rate increases.

Studies have shown that solid materials subjected to high rate or impulsive loading exhibit dramatically enhanced strength. Also, the dynamic strength of geological materials is greater than their static tensile strength. However, violent fragmentation of a body can occur because of dynamic tensile stresses that result from a rapid deposition of energy through contact forces [17,18]. Although compressive loading is helpful in understanding rock breakage, it is the tensile strength that controls rock failure. The tensile strength of rock is only ~10% of the compressive strength [19], due to the presence of pre-existing flaws or cracks within the rock material. In fact, rocks always break in tension under compressive forces with a low energy efficiency associated with the lower tensile components produced under compressive loading. Tromans [2] theoretically estimated a maximum ideal energy efficiency of 7-9% for rock breakage under indirect tension, i.e. comminution equipment, while for straight tensile loading (e.g. blasting) the maximum ideal theoretical efficiency is ~60%.

2.1. High loading rate methods

Hypervelocity projectile impact has received much attention as a high loading rate technique, spurred by interest in the possible effects of meteorites and debris impacts upon space vehicles. Several methods have been explored for acceleration of small projectiles. These include projection by compressed air, explosives, electromagnetic gun, and one and two stage light gas gun. Limitations on the selection of each method include the strength of the gun and projectile, the length of the gun, and the attainable velocity. Currently, a maximum velocity of about 20 km/s for a small projectile is achievable utilizing a three-stage light gas gun [20].

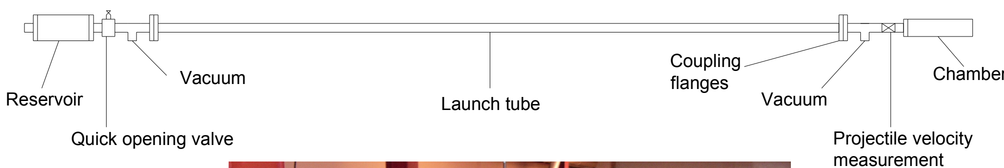
In general, rock breakage testing methods utilize only single particles in order to determine the particle size-energy relationship governing fracture, whereas conventional comminution processes deal with bulk particulate materials with significant interparticle effects that can not be observed in single particle tests. Testing techniques may involve single particle impact velocities of <50 ms^{-1} (Hopkinson bar method) or more than 2 kms^{-1} (two-stage light-gas gun, electromagnetic launcher) [21], [NB. impact velocities in industrial comminution equipment are typically < 10 ms^{-1}].

3. High velocity impact comminution

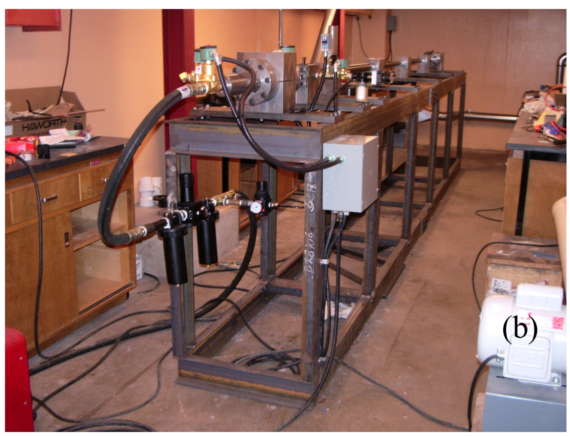
Our objective in the present study is to improve on fragmentation methods and minimize energy use during comminution by examining the behavior of rock material at higher velocity impacts than conventional comminution processes. Accordingly, there is a need to design and construct a new apparatus to test bulk particulate rock samples, instead of a single particle, and to launch a projectile at velocities from 10 to at least 500 ms^{-1}.

The technique utilizes aggregated rock samples fragmented in a confined chamber while subjected to transmission of stress waves produced by the impact velocity of a steel projectile (Fig. 2).

Fig. 2 UBC-CERM3 high-velocity impact facility:
(a) Complete drawing and gas reservoir, (b) Apparatus



(a)



This device is capable of launching the projectile at variable impact velocities measured before the impact by two pairs of laser diode detectors. Laser sensors mounted adjacent to the barrel record the travel time, and thus velocity, which is analyzed to obtain dynamic fragmentation energy for the test materials, together with particle size analysis before and after breakage. The existing air inside the system and between particles is evacuated by a vacuum pump to help launch the projectile without air resistance and also to transfer the stress waves to particles.

3.1. Testwork program

Experiments have been conducted on three different materials – highly porous limestone, quartz with low specific surface area (low porosity), and rock salt with the highest Poisson ratio of all material selected (Table 1). Chunk samples (more than 50 mm in diameter) were crushed, ground and sized until they passed a 2 mm screen size. Bulk samples (-2 mm + 1 mm) were selected to undergo experiments under high velocity impacts in order to make the particle breakage phenomenon as close to that of a real grinding operation as possible. The target chamber in which fragmentation takes place is capable of holding about 5-50 g of material with variable depths for the target bed. Two bed zones with a target bed depth of 75 mm (13 g) and 150 mm (25 g) were established for the experiments. Particle size distribution analysis was carried out after each test for all samples tested at both depths. The representative sample demonstrates the material size before breakage or with zero impact velocity.

Table 1 Properties of rock samples as used in this test work

Rock Type	**Initial Bulk Density (g/cm^3)**	**Poisson Ratio**	**Initial Specific Surface Area (m^2/g)**	**Specific Surface Energy (Jm^{-2})***
Limestone	1.36	0.215	0.728	1.0
Quartz	1.40	0.078	0.005	2.678
Rock Salt	1.28	0.3	0.02	0.577

* (Tromans and Meech)

A Quantachrome surface area analyzer (BET) was used to measure the specific surface area (SSA) of material before and after each test. Previously, the range of changes in SSA as a function of impact velocity has shown significant improvement with increasing impact velocities for all samples [22]. Also, the SSA was enhanced as particle size decreases. The total surface area was then calculated to evaluate the efficiency of breakage considering the retrieved amount of material.

3.2. Energy efficiency model

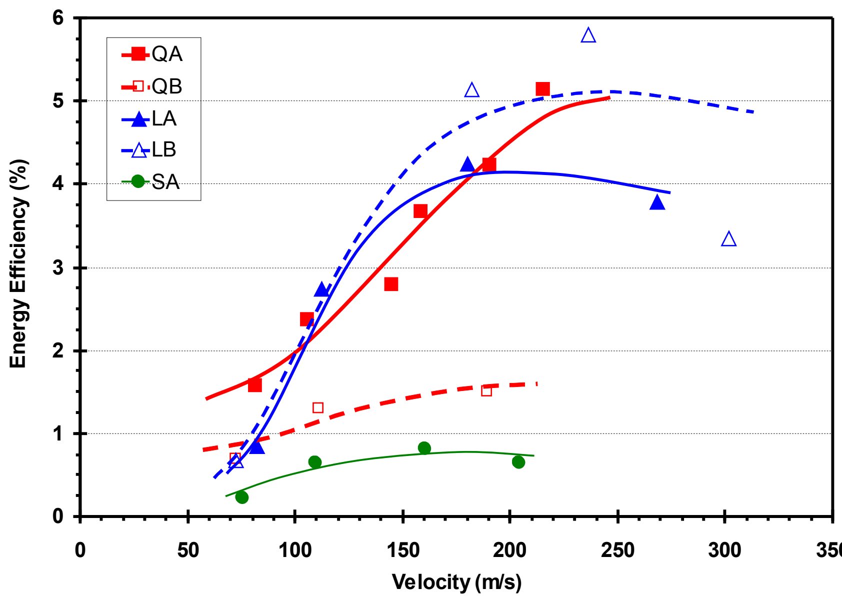
In this model, the energy efficiency of breakage has been defined as the ratio of energy output to energy input [23]. Before and after each test, the surface area of material can be measured. Therefore, the new surface area produced will provide a measure of the total energy output from knowledge about the specific surface energy of the solid material. Energy input can be calculated with the known mass of projectile and its velocity of impact (see Eq.1). The influence of impact velocity on the energy efficiency of rock breakage for all samples tested in both zones is shown in Fig. 3. As can be seen, the efficiency of all samples has been significantly improved with increasing impact velocities. However, it seems that all graphs will decline within the velocity range after passing a peak at around 180-220 m/s. However, it is clear that the energy efficiency trend within the velocity range is doubled or tripled with increasing velocity of impact on rock breakage. Also, no significant improvement in efficiency can be obtained for velocities less than 50 m/s for current comminution problems.

$$\eta = \frac{(SSA_2 - SSA_1)W.S_E}{\frac{1}{2}MV^2} \times 100 = \frac{200(SSA_2 - SSA_1)W.S_E}{MV^2} \qquad \text{(Eq.1)}$$

η = Energy Efficiency (%)

SSA_2 = Specific surface area after breakage (m^2/g)
SSA_1 = Specific surface area before breakage (m^2/g)
W = Weight of sample (g)
S_E = Specific surface energy (Jm^{-2})
M = Projectile mass (kg)
V = Projectile velocity (ms^{-1})

Fig. 3 Comparison of energy efficiencies
(Q=quartz, L=limestone, S=salt; A=75 mm, B=150 mm)



4. Results and discussions

Although rock fragmentation under high velocity impact has been studied for some time, it has been unclear whether an increase in energy efficiency at the same input energy level occurs when strain rates are high. For years, the use of explosives provided a way to break rock in tension with observed efficiencies about one order of magnitude greater than that of comminution. But, it has never been verified until now that high strain rates also provide increased efficiencies in terms of generating new surface area. The current study has demonstrated clearly that the percentage of energy utilized in the generation of new surface area increases with the impact velocity.

4.1. *Impact velocity and energy input model*

In this study, the model of breakage utilizes the kinetic energy content of the projectile (i.e. velocity and mass) to determine the energy efficiency. We found that breakage occurs more efficiently at higher impact velocities than at lower ones. Now, the question remains whether the level of specific energy input (Jg^{-1}) or velocity (ms^{-1}) causes this enhancement? These two factors are related via general energy formulae. The range of energy efficiency as a function of specific energy input and impact velocity are presented in Fig. 4 and 5, respectively.

Fig. 4 Energy efficiency vs specific energy input

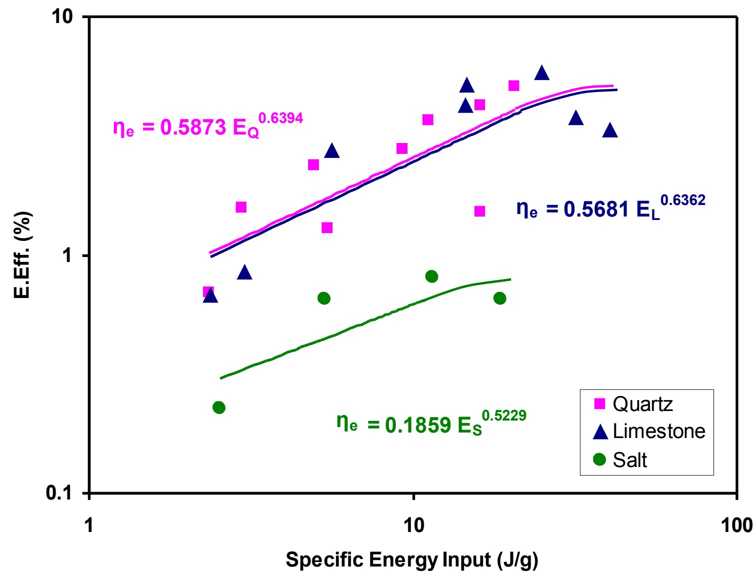
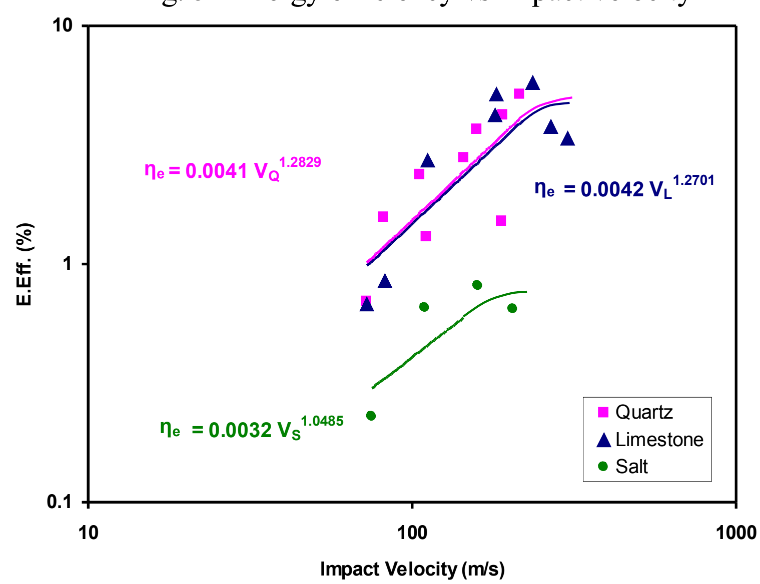


Fig. 5 Energy efficiency vs impact velocity



Note that the trend line for the data set in Fig.4 presents a general rule, as shown in Eq. 2, with an exponent value of around 0.5. Had this exponent been close to 1.0, then energy input would be the determining factor. However, the slope of the trend line is slightly above 0.5 (0.64, 0.64, and 0.52) indicating that the specific energy level does have a small role in overall efficiency.

$$\eta_e = K_e \cdot \sqrt{E_i} \qquad \text{(Eq.2)}$$

η_e = Energy efficiency (based on energy input) (%)
E_i = Specific Energy Input (J/g)
K_e = Energy Index (% $g^{\frac{1}{2}} / J^{\frac{1}{2}}$) or (% $(g/J)^{0.5}$)

Also, the trend line for data set in Fig. 5 presents an equation with an exponent value of close to 1.0 (see Eq. 3). A slope near 1.0 indicates that velocity is the determining factor. But because the exponent lies above 1.0 (1.3, 1.3, and 1.0) it means that energy also has an effect. Since energy input is a function of velocity squared, it is clear that efficiency of breakage is related directly to the impact which must translate into the velocity of the propagating cracks.

$$\eta_v = K_V . V^1 \qquad \text{(Eq.3)}$$

η_v = Energy efficiency (based on impact velocity) (%)
V = Impact velocity (m/s)
K_v = Velocity Index (% s/m)

These equations are empirical with validity over the range of impact velocity measurements, i.e. 50 to 250 m/s (*i.e.* in a dynamic regime). The energy index (K_e) and velocity index (K_v) are also empirical parameters affected by many factors such as type of material, material characteristics, mechanical properties of the material, Poisson's ratio, grain size, density, porosity, environment. To determine these factors, a large number of similar tests with different materials and different variations are required. Also, the experiments should be extended to higher and lower velocities than those in the current study in order to measure the value of K_e and K_v over an extended dynamic range. Similarly, parallel experiments should be performed to establish K_e and K_v in the static range.

5. Conclusion

Our studies have attempted to merge impact engineering as a solution for mining and comminution problems in terms of rock breaking. In dynamic fragmentation, a high-velocity impact comminution apparatus was designed and built to directly measure the quantitative parameters of impact velocity on aggregated rock materials. Experiments on three rock materials - porous limestone, quartz, and rock salt, were conducted at projectile velocities from 50 to 300 m/s. The results suggest energy efficiency of rock breakage is improved by as much as 2 to 3 times under high velocity impact.

To summarize, the following results can be concluded:

1. Utilization of high strain rates and high-velocity impact in comminution provides an opportunity to improve energy efficiency in rock breakage.
2. Regardless of mineralogy, high-velocity impact helps to explain the reported increase in efficiency of the higher impact crushing technologies (high pressure grinding rolls (HPGR), Barmac, and roller crushers).
3. Impact velocity is the key to enhancing the efficiency of rock fragmentation and has an important effect independent of total energy input.
4. Future work should focus on designing new devices to increase impact intensity during comminution.

6. References

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