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# The influence of equipment settings and rock properties on high voltage breakage

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#### ABSTRACT

High voltage breakage is a novel comminution method that relies on highly energetic electrical pulses to weaken or fully fragment rocks. The potential of this technology to improve liberation and increase the grindability of ores has been demonstrated previously, but the fragmentation process is not fully understood. In this study a total of 20 rock types were treated in a SELFRAG Lab device to determine the influence of equipment parameters on breakage. Rock mass properties and Bond Work Index were determined for each rock type to identify their relation to breakage behaviour. Results show how, by influencing total applied energy, the number of discharges and voltage are the two major influences on the resultant product size. It has also been shown that coarser feed sizes are more amenable to high voltage breakage. Acoustic impedance, porosity and quartz content were found to relate to breakage but Bond Work Index only correlates loosely.

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# 1. Introduction

Tromans (2008) and Norgate and Jahanshahi (2011) have highlighted the energy inefficiency of comminution processes. Improving comminution efficiency has been the focus of much research in recent years and initiatives with this goal include a platform to discuss energy use in comminution and raising awareness of the issue (Coalition for Eco-Efficient Comminution), extensive scientific research aiming to optimise energy utilisation of existing processes and development of new technologies.

High voltage discharges to pre-weaken or fully fragment rocks offers a new technology with considerable potential. It is a relatively novel comminution technique that may improve energy utilisation in comminution through improved liberation, less fines generation and weakening of rocks prior to grinding (Wang et al., 2011, 2012). The technology relies on inducing electrical breakdown, which occurs when the resistivity of a dielectric is insufficient to completely block all transfer of electricity, whilst conductivity is not high enough to fully accommodate this flow of electricity without considerable changes to the crystal lattice.

The Marx generator, crucial for development of high voltage pulses, was invented in 1924 by Erwin Otto Marx. However, it was not until the Cold War era that Russian scientists realised its potential in mineral processing, after a chance discovery that high voltage discharges in water generated shockwaves powerful enough to crush rock (Andres, 2010). This form of high voltage breakage (characterised by slower pulse rise-times), better known as electro-hydraulic crushing, was later superseded by the more efficient electro-dynamic technology under investigation in this paper, which uses faster pulse rise-time electrical discharges to induce electrical breakdown in the rock rather than in water. For a more in-depth description of the early history and evolution of high voltage breakage technology, readers are referred to Andres (2010).

In the 1990s, several research institutions, including the Forschungszentrum Karlsruhe (FZK), Germany and Imperial College, London, embarked on research programs investigating high voltage breakage technology, its potential applications and commercial prospects. Mineral processing applications were the focus of the work at Imperial College, whilst FZK concentrated on industrialisation of high voltage breakage products in a variety of specific applications. In 2007 SELFRAG acquired licences for the technology from FZK and embarked on an extensive research and development programme to market high voltage equipment for the minerals and materials processing industries. Parallel to research at FZK and Imperial College London, a consultancy (CNT-MC) based in Canada also carried out research (e.g. Rudashevsky et al., 1995, Lastra et al., 2003) into the technology.

Interest in this technology has increased significantly in recent years, whilst most work has focussed on proof-of-concept, with little systematic investigations into underlying processes. Andres et al. (2001a,b) and Wang et al. (2011, 2012) have demonstrated the potential of high voltage breakage as a mineral processing technology. Andres et al. (2001a,b) and Wang et al. (2012) focused on using high voltage breakage technology for full fragmentation, whereas Wang et al. (2011) focused on using the technology to

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weaken rocks. Andres et al. (2001a) reported improvements in grades and/or recoveries after high voltage treatment for copper, nickel and platinum-group element ores. Specific energy inputs for the different tests were not reported, but in a subsequent paper Andres et al. (2001b) reported energy consumption was nearly two times as high as that for mechanical comminution of the same ore (90 vs. 50 kW h  $t^{-1}$ ). In a more recent publication, Andres (2010) provided a compilation of other promising results on flotation and leaching behaviour of fragmented ores to highlight the potential of high voltage breakage technology. Wang et al. (2012) performed an extensive investigation using a Mineral Liberation Analyser (MLA) to compare liberation from high voltage breakage and mechanical comminution at the same specific energy input. They found high voltage breakage produced significantly coarser products with better liberation of the minerals of interest. They suggested there may be an optimal range of specific energy application in high voltage breakage that would yield the required liberation of target minerals. A different approach was taken by Wang et al. (2011), who used a Rotary Breakage Tester (JKRBT) to determine product residual hardness after high voltage treatment of between 1 and 3 kW h  $t^{-1}.$  They found a weakening of 9–52% after treatment and predicted energy savings of up to 24% during the comminution process. It is unknown whether improved liberation such as that found by Wang et al. (2012) is still available at these lower energy inputs. The positive energy balance of the weakening approach has made it the preferred route for using high voltage breakage in processing circuits. Construction of a 100t/h demonstration plant is underway and the ultimate goal is manufacturing continuous equipment with industrial-scale (>500 t/h) throughput for weakening of rocks.

Fragmentation processes during high voltage breakage are distinctly different from those in mills and crushers. According to Andres et al. (2001b) plasma channels form within the dielectric solid during electrical breakdown. These channels undergo explosive radial expansion, giving rise to powerful shockwaves that result in micro-crack formation and ultimately may cause fragmentation of the solid. Bluhm et al. (2000) also postulated that the high voltage-induced fragmentation process relies largely on shock waves and induced tensile forces, causing breakage at inhomogeneities when tensile strength is exceeded, but experimental data to support this is limited. However, in an earlier paper, Andres et al. (2001a) attributed micro-crack generation and mineral liberation to plasma capillaries, implying that there is a significant component of direct fragmentation action by the plasma. This dichotomy demonstrates that further experimental work is needed to clarify high voltage breakage processes. In addition, little data have been published on the effect of equipment settings on fragmentation, selective fragmentation and weakening, and how these factors interact with rock properties. These data are essential in designing effective processing configurations and protocols and may provide limitations to the use of high voltage breakage equipment in certain applications.

This paper aims to clarify some of these aspects of the technology and aid optimisation of process variables. This was done by investigating the influence of equipment settings and feed size on the resultant product after high voltage treatment. Other factors such as selective fragmentation, fines reduction and product shape are not discussed further. The focus of this paper is on the effects of voltage and the total number of discharges, as these are the two ways of varying total energy input, but some observations relating to electrode gap and pulse rate will also be discussed. During the tests it was also found that there was a strong effect of feed size on fragmentation behaviour. With current work to scale up high voltage breakage technology in mind, results presented in this paper will be discussed in terms of up-scaling and integration of the technology into a processing circuit.

#### 2. Methods

### 2.1. Feed material

The rock types used as feed material in this study were selected to give a broad spectrum in properties and genetic origins. Initial work was carried out on rock types used for aggregate production because of their relatively simple and uniform mineralogy. Sulphides in particular tend to have more variable electrical properties (mainly permittivity) when compared to common rock-forming minerals and at the outset of the study it was uncertain how this would interact with breakage behaviour in the high voltage regime. To minimise any potential complications due to the presence of sulphides, these rocks were used as the feed material for initial experiments. Later tests on mineral ores were performed to compare and contrast their behaviour to that of the aggregates and to reinforce the link to mineral processing applications.

Most rocks were obtained as lump material to allow core extraction for geomechanical testing. The remainder of the rocks were stage crushed to the desired feed size. The feed size for most tests was -20 + 14 mm, with the exception of the material for those tests where feed size was the variable under investigation. Aggregates were checked for uniformity and any rocks of unusual appearance were removed by automated optical sorting.

## 2.2. High voltage treatment

The high voltage treatments were performed in batches in a SELFRAG Lab unit, manufactured by SELFRAG AG, Switzerland (Fig. 1). The device relies on a transformer feeding a Marx generator to generate pulses and discharge them into a process vessel. This process vessel sits on a lifting table that moves it into a shielded processing area. The process vessel can be used in open and closed configuration. The closed configuration utilises a closed bottom electrode as opposed to the open configuration where the bottom electrode is basically a sieve deck with a separate sample collection chamber underneath. The open configuration allows material of the desired grain size through, which prevents them from further disintegration and using spark energy for breakage beyond the target size.

In the SELFRAG Lab unit, the voltage (90–200 kV), electrode gap (10–40 mm), pulse rate (1–5 Hz) and number of electrical pulses (1–1000) can be varied, and it is designed for batch processing of samples of up to approximately 1 kg. For this research the high voltage treatment was carried out on batches of 700 g in a closed vessel with de-mineralised water as the medium (conductivity <10  $\mu$ s/cm).

Prior to initial testing, standard test settings were defined in conjunction with SELFRAG. The number of discharges was set at 300 with a voltage of 140 kV, a pulse rate of 3 Hz and with an electrode gap of 25 mm. At these settings, all particles are affected and discharges can reliably be achieved. Table 1 outlines the settings for the different test series. For all tests where the effect of a single variable was being investigated, three out of four settings were kept constant whilst the variable of interest was being varied. In addition, a factorial design experiment was carried out on a porphyry copper ore to identify possible interactions between voltage and number of pulses. In this test, feed size, electrode gap and pulse rate were kept the same as for the other tests, and 20, 50, 100 and 300 discharges were applied each at 110, 140 and 180 kV.

There is an inefficiency involved in the generation and transfer of the high voltage pulse which means that the energy consumption by the machine (generator energy) is higher than the energy discharged into the process vessel (spark energy). This inefficiency is largely due to several safety features in the lab-scale equipment



Fig. 1. Schematic of SELFRAG Lab unit.

Table 1				
Equipment se	ettings for	the diff	erent test	setups.

Test variable	Voltage (kV)	No. of discharges	Electrode gap (mm)	Pulse rate (Hz)
Voltage	90-200	300	25	3
No. of discharges	140	5-850	25	3
Electrode gap	140	300	10-40	3
Pulse rate	140	300	25	1–5
Factorial design	110, 180	20, 50, 100, 300	25	3
Feed size	140	300	25	3

and the fact the whole setup is geared towards ease of use and minimal sample loss, rather than process efficiency. As the Lab unit is a batch processing device, the relatively small throughput means many of the losses are large compared to what they would amount to in continuous equipment in terms of energy loss per tonne of capacity. In addition, many causes of inefficiency can largely be eliminated through different electrode and Marx generator setups. Leaving equipment-related factors out of the equation, the difference between generator and spark energy is dependent on process water conductivity (high process water conductivity reduces discharge ratio), the rock being treated and equipment settings.

In this paper, reported energy levels refer to the spark energy input. When assessing the economics or efficiency of high voltage breakage technology it is recommended that generator energy input is relied upon, but for this research spark energy input is preferred as it leaves out of the equation machine-specific influences and pulse/discharge inefficiencies.

# 2.3. Analysis of treated rocks

The main analysis of the high voltage treated products involved dry sieving on a standard  $\sqrt{2}$  series of sieves from 355 µm to 45000 µm. Care was taken to recover the full sample, including fines, after high voltage treatment. Cubic splines were used to calculate the 80% passing size ( $P_{80}$ ), >14000 µm fraction and fines fraction from the available data. Statistical processing of the data, such as curve regression and dataset comparison, was carried out using SPSS software. For the latter, the Wilcoxon Signed Ranks test was used because the assumption of normality required for standard paired-sample *t*-tests could not always be guaranteed.

Analyses in this paper focus on product size. Other attributes, such as selective fragmentation, particle shape after treatment, fines generation and change in physical properties of the particle (i.e. weakening) and how these attributes interact with equipment settings and material properties may also be of interest and are recommended for consideration in further research.

# 2.4. Rock properties

Cores were extracted from lump material to facilitate geomechanical testing, with a minimum of three cores tested per rock type. Dimensions and weight were determined accurately for each core to give density (kg  $m^{-3}$ ), and sound velocity (m  $s^{-1}$ ) of the rocks was measured using a Posso acoustic tester. These two values were used to calculate acoustic impedance (i.e.  $Z = \rho C_0$ , where  $\rho$  is the density and  $C_0$  is the speed of sound in a material). These cores were then used to determine average uni-axial compressive and tensile strengths (Brazilian test) in a rigid load frame. Young's Modulus was determined from the load profile obtained during the compressive strength tests. Irregularly shaped particles and off-cuts from cores were used for determination of the Point Load Index. For all geomechanical test work, guidelines by the International Society for Rock Mechanics were followed (ISRM, 1981). The Bond Ball Mill Work Index was determined following a guideline by Deister (1987) at a closing size of 355  $\mu$ m, with the sample for these tests derived from the same sample batch or lump material as the rock treated in the SELFRAG Lab unit.

Quartz and sulphide content, porosity and characteristic grain size were determined from QEMSCAN analysis of polished thin sections. The QEMSCAN 4300 was operated in fieldscan mode, running at an X-ray pixel spacing of 10 µm in conjunction with iMeasure v4.2 and iDiscover v4.2 and v4.3 software for data acquisition and processing. General operational procedures for sample preparation and data processing/analysis, as outlined in Pirrie et al. (2004) and Rollinson et al. (2011), were followed. Quartz and sulphide content are determined during X-ray analysis and the porosity was calculated by classing internal background, glass and resin within a sample as porosity (injector function). Data from QEM-SCAN investigation are considered a semi-quantitative indication because of the 2-dimensional nature of the sample measured, the relatively limited amount of data and potential stereological errors. Furthermore, given the 10 µm X-ray pixel spacing during analysis, it is only relevant to the >10  $\mu$ m portion of porosity. Armitage et al. (2010) report a comparison of porosity data from QEMSCAN and mercury porosimetry, showing that QEMSCAN can be used to



Fig. 2. Whole sample product size as a function of the number of discharges. Voltage (140 kV), electrode gap (25 mm), feed size (-20 + 14 mm) and pulse rate (3 Hz) kept constant.



Fig. 3. Whole sample product size as a function of the voltage. No. of discharges (300), electrode gap (25 mm), feed size (-20 + 14 mm) and pulse rate (3 Hz) kept constant.

determine porosity, though it does tend to underestimate it. The QEMSCAN iDiscover software calculates average grain size by adding up the total length of all the horizontal intercepts for a mineral grain measured in a sample and divides by the number of intercepts for that grain to give an average grain size per mineral. From the QEMSCAN data, characteristic grain size for the whole sample was calculated by weighting the reported grain size of a mineral by its mineral volume as reported by iDiscover software.

# 3. Results and discussion

# 3.1. Equipment settings

# 3.1.1. Number of discharges and voltage

The voltage applied to a sample determines the amount of energy deposited per discharge and each discharge represents an incremental amount of additional spark energy. For purposes of clarity it is important to make a distinction between pulses (every electrical burst of energy generated by the Marx generator) and discharges (only those pulses that induce electrical breakdown in the rock sample). The SELFRAG Lab unit can be set to produce any discrete number of electrical pulses, but not each electrical pulse develops into a discharge affecting the rock (i.e. not all pulses induce electrical breakdown in the rocks).

Fig. 2 shows the influence of the total number of applied discharges on the product size after high voltage treatment. Invariably, each rock type exhibited an initial phase (up to approximately 75 discharges or 7 kW h t<sup>-1</sup>) where little size reduction occurred, followed by a strong decrease in product size over a relatively small energy range, before levelling off in the high energy range. This trend was observed for every single rock type. The influence of voltage on product size is illustrated in Fig. 3. An important observation is that, especially at lower voltages (<120 kV), a large number of pulses may be needed to achieve the desired number of discharges (up to 1800 pulses to achieve 300 discharges). For some rock types discharges can easily be achieved at voltages as low as 90 kV (hornfels, quartz monzodior-



**Fig. 4.** Comparison of whole sample product size after treatment with voltage or no. of discharges as main variable under investigation. Electrode gap (25 mm) and pulse rate (3 Hz) kept constant.

ite) whereas others need voltages in excess of 110 kV to achieve any discharges (granite, tuff, dolerite).

The number of discharges and the applied voltage are both directly proportional to the energy input into a sample during high voltage breakage. An important question therefore is whether treatment at different voltages but similar total spark energy inputs yields comparable particle size distributions. Fig. 4 combines data from Figs. 2 and 3 and shows that both distributions display similar trends, though the voltage tests span a smaller energy range (as a consequence of test setup). Further statistical analysis, comparing the measured and predicted product size showed that in a case-by-case analysis on six rock types, only one (quartz monzodiorite) showed significant deviation from the predicted product size.



**Fig. 5.** Whole sample product size as a function of spark energy input applied through different voltages for a porphyry copper ore. Electrode gap (25 mm) and pulse rate (3 Hz) kept constant.

To further examine the effect of voltage, factorial design-style experiments were done on a porphyry copper ore and a goldbearing quartz monzodiorite, with different combinations of discharges (20, 50, 75, 300) at three voltages (110, 140 and 180 kV). Figs. 5 and 6 shows the result from these tests. For both ores there is no significant difference between particle size distributions after treatment at 140 and 180 kV. However, for both test series the highest energy 110 kV test had a significantly coarser particle size distribution than predicted for 140 kV and 180 kV treatments. Moreover, when comparing tests for these two rock types where the voltage was the sole variable of interest, the particle size distributions from treatments below 130 kV all yielded coarser products than expected. This behaviour is most pronounced in the monzodiorite but can also be observed to a lesser extent in the porphyry copper ore.

The discharges–voltage comparison results suggest that total applied energy is the main variable to consider for product size distribution, but that at lower voltages the rate at which particles get broken out of the feed fraction may be lower. The applied voltage governs energy per discharge, and it may be that a 'threshold' voltage is required to fully overcome particle strength and directly cause breakage. Below this threshold voltage particles still accrue incremental damage but it may take multiple discharges to disintegrate particles enough to make them report to a size fraction below that of the feed. The monzodiorite has a comparatively high tensile strength, which may contribute to this behaviour but more detailed investigations are recommended to ascertain the cause of the effect. It is also inconclusive whether certain voltage/discharge combinations yield more or less pronounced pre-weakening and if liberation is affected.

# 3.1.2. Total energy input

No general relationship could be defined that described product sizes from both breakage over the entire energy input range, so the data were separated into two distinct datasets. The first considered the percentage of feed size remaining (i.e. the weight of the >14 mm fraction); the second dataset considered the particle size distribution of the product.



**Fig. 6.** Whole sample product size as a function of spark energy input applied through different voltages for a gold ore. Electrode gap (25 mm) and pulse rate (3 Hz) kept constant.

Fig. 7 shows the decrease in weight percentage of >14 mm particles with spark energy input (W). The rate of decrease followed an exponential relationship for every rock type tested:

% of feed remaining = 
$$C_e \exp^{-Se W}$$
 (1)

where  $S_e$  is a material-dependent exponent that determines the steepness of the function describing breakage of the >14 mm fraction and  $C_e$  is a constant. For most rock types the constant was close to 1 (i.e. no particles in the <14 mm fraction at no energy applied), so the constant is not included in this relationship. The majority of particles in the coarsest size fraction (>14 mm) showed little or no sign of being affected by high voltage pulses. As energy inputs increase (i.e. more discharges applied), the probability of a particle being affected by a discharge increases, and this may be reflected in the exponential nature of the distribution. However, the slope of this relationship was also found to vary significantly between rock types and Section 3.3 outlines efforts to relate feed size breakage to rock properties. With the exception of two rock types (insufficient data in the <20 kW h t<sup>-1</sup> range), the correlation coefficient for each rock type exceeded 0.80 (mostly >0.95) and all fits were highly significant (p < 0.01).

The 80% passing size of the product (<14 mm) for all 20 investigated rock types are shown in Fig. 8. At energy levels above 5 kW h t<sup>-1</sup> the decrease of particle size distribution with spark energy input can be described by a power/fractal law:

Product 
$$P_{80} = C_f W^{-Sf}$$
 (2)

where  $C_f$  is the rock-specific constant, and  $S_f$  is the rock-specific exponent.

Table 2 lists the fitted parameters Se and Sf for each of the tested rock types. Each rock-specific relationship had a correlation coefficient above 0.85 and the significance was below 0.01. Links between these rock-specific energy–size relationships and rock properties are discussed in Section 3.3. Between 0 and circa 5 kW h t–1 of spark energy applied, there is a phase where size reduction does not fit the power/fractal law. This is thought to reflect an initial breakage phase where the majority of particles have not yet accrued sufficient damage to report to the <14 mm fraction. When affected by a discharge, micro-cracks are formed in a particle and some spalling may occur. Once enough energy has been applied (and depending on particle properties), micro-crack density is thought to increase sufficiently to produce an interconnected

fracture network, eventually reducing a particle's integrity to the point where it fragments completely.

The amount of generator energy released by the Marx generator can be calculated accurately from the applied voltage and the number of discharges, regardless of rock type. The amount of spark energy transferred to in a sample can also be accurately calculated from these two variables, but there is considerable variation between rock types, which suggests the conversion of generator to spark energy is rock-specific. Generator-spark energy conversion ratios were observed ranging from 80% to 90% range (sandstone, iron ore) to <60% (soapstone) and were used as a measure of the efficiency of the conversion process.

#### 3.1.3. Electrode gap and pulse rate

The other two equipment settings that can be varied in the SEL-FRAG Lab unit are the electrode gap (distance between discharge and ground electrode in the processing vessel) and pulse rate (no. of pulses per second).

It was found that at certain processing parameters (typically low voltage gradient/high processing water conductivity), a portion of pulses from the Marx generator did not develop into discharges. Generation of each pulse consumes a fixed amount of energy, regardless of whether a discharge is developed and consequently every 'misfired' pulse (i.e. no discharge) represents lost energy.

By definition, the discharge ratio (no. of discharges divided by number of pulses) cannot exceed 1 and in the available dataset it ranged from 1 down to 0.6 for most rock types tested. The conversion of generator energy to spark energy (i.e. spark energy divided by generator energy) was used as an indicator of electrical efficiency of high voltage breakage. Fig. 9 shows at discharge ratios smaller than 0.95, a linear decrease ( $r^2 = 0.84$ , sig. < 0.001) of electrical efficiency was observed with a decrease in the discharge ratio. Therefore, this ratio is a key factor to consider in optimisation of the electrical efficiency of high voltage breakage. Above a discharge ratio of 0.95 the electrical efficiency varied from approximately 0.6 to >0.9 depending on the rock type.

The electrode gap can influence breakage through two different routes. Firstly, it governs the volume in the processing vessel available for particles. This volume accommodates not only the physical size of the particles, but also their movement. A low electrode gap may restrict particle movement, resulting in a relatively small number of particles receiving the bulk of the energy whilst other



Fig. 7. Mass percentage of particles left in the feed (>14 mm) fraction as a function of total spark energy input for 20 different rock types. Voltage (140 kV), electrode gap (25 mm) and pulse rate (3 Hz) kept constant.



Fig. 8. Product size for the <14 mm fraction as a function of spark energy input for 20 different rock types. Voltage (140 kV), electrode gap (25 mm) and pulse rate (3 Hz) kept constant.

Fitted parameters $S_e$ and $S_f$ for all 20 rock types. $S_e$ for pegmatite not available due to
insufficient data points for a statistically significant fit.

	Se	$S_f$
Altered metagabbro	-0.170	-0.957
Andesite	-0.131	-1.387
Chert	-0.158	-1.008
Dolerite	-0.153	-0.933
Gneiss	-0.138	-0.879
Granite (fine-grained)	-0.199	-1.477
Granite (medium-grained)	-0.259	-1.274
Granite (porphyritic)	-0.262	-1.296
Granodiorite	-0.199	-1.229
Hornfels	-0.175	-1.034
Limestone	-0.285	-1.065
Iron ore (BIF)	-0.241	-1.217
Metagabbro	-0.152	-0.891
Pegmatite	n/a	-1.183
Quartz monzodiorite	-0.148	-1.213
Sandstone	-0.140	-3.341
Shale/massive sulphide	-0.130	-1.402
Slate	-0.206	-1.634
Soapstone	-0.345	-1.601
Tuff	-0.192	-1.146

particles are left largely unaffected. Observations suggest the manifestation of the effect of electrode gap on product size is complex. The product size for some rock types is completely unaffected by variations in electrode gap, whereas other rock types show varying degrees of dependence on electrode gap. Where electrode gap was found to influence product size, the lower electrode gaps (i.e. higher voltage gradient but less space for particle movement) yields the coarser product. This implies the effect is mainly caused by volume restrictions. Secondly, the electrode gap is of direct influence on the voltage gradient between electrodes. Electrical breakdown is a stochastic process and for this to occur the voltage gradient needs to exceed the electrical breakdown strength of a material (both denoted in kV mm<sup>-1</sup>). The probability of breakdown occurring increases with voltage gradient till it is close to or at 1. Fig. 10 shows the discharge ratio as a function of voltage gradient. Below a voltage gradient of 7 kV  $mm^{-1}$ , the discharge ratio was found to vary strongly between 0.2 and 1. Above this, the discharge ratio was always larger than 0.95.

The pulse rate was not found to cause significant deviations of particle size distribution from what was expected from the en-



**Fig. 9.** Efficiency of conversion of generator to spark energy as a function of discharge ratio for discharge ratios below 0.95.

ergy-size relationship. However, it was observed that a higher pulse rate made development of a discharge from the high voltage pulse more probable. Fig. 11 shows this effect for a rock type treated at 100 kV/25 mm electrode gap, which is near the minimum voltage gradient required to achieve breakdown for this rock type. This effect has been observed for other rock types, though its magnitude may vary depending on a rock's breakdown voltage and the operating conditions. The SELFRAG Lab unit has a pulse rate range of 1–5 Hz, so it is unknown whether there is an upper limit to the influence of pulse rate on the discharge ratio. Plasma effects and dissipation of electrical charge happen on a much shorter time scale (<ms), so the pulse rate effect is likely related to residual bubbles in the process water after a discharge (Giese and Muller, pers. comm.). At higher pulse rates these bubbles may not have collapsed fully, or a transient product may still reside in the processing area. The breakdown strength of gaseous phases in these bubbles is lower than that of water, and therefore they should provide an alternative path, facilitating transfer of a discharge into the rock sample that might otherwise not have developed breakdown in the rock sample.



Fig. 10. Discharge ratio as a function of voltage gradient for 11 rock types. No. of discharges (300) and pulse rate (3 Hz) kept constant.



**Fig. 11.** Discharge ratio as a function of pulse rate for quartz monzodiorite. Voltage (100 kV), no. of discharges (300) and electrode gap (25 mm) kept constant.

# 3.2. Feed size

Fig. 12 shows feed size (represented through mean feed size)was shown to have a very distinct effect on reduction ratio  $(F_{80}/P_{80})$ . This feed size effect is so pronounced that the coarsest feed sizes invariably produce a finer product size distribution than the smallest tested feed size after the same total spark energy applied. This shows that coarser particles are far more susceptible to high voltage breakage than finer feed sizes, and suggests that the whole volume of individual particles are affected during high voltage breakage. During breakage of coarse particles, the progeny will at some stage contain particles similar to the finer feed sizes. This would present a physical limit to size reduction if the feed size effect occurred mostly concurrent with breakage and result in all feed sizes producing similar product sizes but this is not the case. This suggests the particle accrues the damage necessary to produce the finer size distributions prior to actual size reduction, as otherwise they would not be comminuted to sizes smaller than that for smaller feed sizes. Stronger field distortions and more complex shock wave interactions and reflections in larger particles may be possible causes for the strong feed size dependence of high voltage breakage.

Energy transfer may also contribute to the observed feed size effect. It is conceivable that a larger particle can provide the full bridge for a discharge from discharge to ground electrode. In this case, all the energy is deposited in this particle, with a relatively limited travel distance through the processing water and consequently less energy loss in the transfer process. Smaller particles on the other hand will not be able to bridge the gap between electrodes fully and therefore sparks may be required to jump from particle to particle several times, involving a longer total travel distance through water. During this process a larger portion of energy may therefore be lost in the water and consequently less energy would end up being available for fragmentation. This mechanism assumes there is sufficient energy in a 140 kV discharge to cause significant damage in a particle regardless of size as the energy/size ratio would otherwise favour smaller particles. Validation of the proposed mechanisms is required as experimental evidence cannot conclusively demonstrate which processes cause the observed effect.

It can also be seen that the feed size effect was evident at varying magnitudes for each of the five rock types tested. The difference in product size between the larger feed sizes (larger than -20 + 14 mm) is minimal. The feed size effect has substantial consequences for integration of high voltage breakage technology into existing processing circuits and will be discussed in more detail later. In the SELFRAG Lab unit there is a physical limitation to the largest feed size (approximately 45 mm) that can be fitted into the SELFRAG Lab processing chamber so it is uncertain what happens above this size.

# 3.3. Rock properties

The slope of the exponential relationship describing the weight percentage of particles left in the feed size ( $S_e$ , see Eq. (1)), and the slope of the power law describing product size ( $S_f$ , see Eq. (2)) were used as measures of rock's response to high voltage breakage. For curve regression purposes, the positive value of the rock-specific exponents was used. Tables 3 and 4 list geomechanical and mineralogical properties of the rocks used in this research. Fig. 13 shows the slope of the exponential decrease relationship for feed size as a function of tensile strength. The general set of data show a linear relationship between the two variables. The outliers are the sandstone (top left) and iron ore (bottom right), and their presence may be explained by their relatively low and high density. The electrode gap was not varied in these tests, and therefore the volume of sample accommodated in the treatment zone between the electrodes



Fig. 12. Reduction ratio as a function of mean feed size for eight different rock types. No. of discharges (300), voltage (140 kV), electrode gap (25 mm) and pulse rate (3 Hz) kept constant.

Table 3					
Geomechanical properties	of the tested	rock types,	including	standard	deviations.

	Bond work index $(kW h t^{-1})$	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)	Density (kg m <sup>-3</sup> )	Point Load Index (IS <sub>50</sub> )	Acoustic impedance $(\text{Kg s}^{-2} \text{ m}^{-1})$
Altered metagabbro	23.4	118 ± 32	13.5 ± 2.6	68.3 ± 4.2	2889 ± 160	11.2 ± 2.2	$1.74\times10^7\pm1.7\times10^6$
Andesite	17.3	n/a <sup>a</sup>	$8.1 \pm 2.5^{b}$	56.9 ± 17.4 <sup>c</sup>	2787 ± 42	10.8 ± 3.2	$1.24\times10^7\pm2.1\times10^6$
Chert	23.1	116 ± 50	19.6 ± 9.8	59.3 ± 7.4	2695 ± 10	15.1 ± 6.9	$1.49\times10^7\pm1.3\times10^5$
Dolerite	24.0	185 ± 46	13.7 ± 4.6	50.9 ± 9.2	2775 ± 36	$9.9 \pm 2.2$	$1.66\times10^7\pm5.2\times10^5$
Gneiss	n/a	137 ± 38	15.6 ± 3.3	140.1 ± 81.7	2927 ± 30	10.8 ± 3.1	$1.84\times10^7\pm7.8\times10^5$
Granite (fine-grained)	11.7	252 ± 21	13.7 ± 1.4	$57.4 \pm 0.4$	2626 ± 3	11.8 ± 2.0	$1.43\times10^7\pm1.9\times10^5$
Granite (medium-grained)	14.4	188 ± 10	11.6 ± 1.7	54.5 ± 3.0	2647 ± 10	7.8 ± 1.5	$1.44 imes10^7\pm1.1 imes10^5$
Granite (porphyritic)	14.8	150 ± 3	9.9 ± 1.1	49.1 ± 2.3	2634 ± 5	7.1 ± 1.5	$1.37\times10^7$ ± 4.1 $\times$ $10^5$
Granodiorite	12.8	146 ± 38	11.7 ± 2.9	44.3 ± 10.0	2653 ± 42	11.5 ± 3.0	$1.34\times10^7\pm8.8\times10^5$
Hornfels	17.1	227 ± 59	15.4 ± 3.3	58.2 ± 6.7	2871 ± 19	10.7 ± 4.3	$1.69  imes 10^7 \pm 9.0  imes 10^5$
Iron ore (BIF)	18.3	136 ± 146	24.0 ± 12.2	$63.4 \pm 56.2$	4021 ± 205	$10.0 \pm 3.7$	$2.00\times10^7\pm3.0\times10^6$
Limestone	9.0	152 ± 48	9.1 ± 2.6	64.2 ± 3.8	2710 ± 6	$6.0 \pm 2.1$	$1.68\times10^7\pm5.6\times10^5$
Metagabbro	17.5	186 ± 41	15.5 ± 2.1	73.7 ± 1.9	2860 ± 11	$10.8 \pm 3.4$	$1.85 \times 10^7 \pm 3.1 \times 10^5$
Pegmatite <sup>***</sup>	n/a	n/a	n/a	n/a	2696 ± 21	n/a	$1.27\times10^7\pm6.6\times10^5$
Quartz monzodiorite*	12.3	212 ± 46	15.4 ± 3.0	58.3 ± 6.5	2781 ± 51	10.9 ± 3.0	$1.51\times10^7$ ± $1.6\times10^6$
Sandstone	3.7	107 ± 5 <sup>a</sup>	$6.6 \pm 0.4$	$26.0 \pm 1.0$	2357 ± 3	$4.5 \pm 0.6$	$0.84\times10^7\pm7.1\times10^4$
Shale/massive sulphide <sup>*</sup>	13.2	n/a	$10.7 \pm 4.0^{b}$	46.3 ± 11.8 <sup>c</sup>	2899 ± 1	8.1 ± 3.1	$1.15  imes 10^7 \pm 1.9  imes 10^6$
Slate	n/a	167 ± 28	$11.0 \pm 4.7$	50.8 ± 21.0	2789 ± 8	9.7 ± 3.8	$1.21\times10^7\pm3.6\times10^5$
Soapstone	n/a	88 ± 4	$3.4 \pm 0.3$	$25.6 \pm 0.4$	2839 ± 5	2.3 ± 1.2	$0.95\times10^7\pm1.6\times10^5$
Tuff	15.7	105 ± 14	$10.0 \pm 1.5$	$47.6 \pm 1.4$	2706 ± 5	$6.8 \pm 2.8$	$1.48\times10^7\pm1.4\times10^5$

\* Gold ore.

\*\* Copper ore.

\*\* Tantalum/Lithium ore.

<sup>a</sup> Compressive strength estimated from co-linearity with point load index.

<sup>b</sup> Tensile strength estimated from co-linearity with point load index.

<sup>c</sup> Young's Modulus estimated from acoustic impedance using Hooke's Law.

remained constant. As a consequence, more mass in this 'hot' zone where the majority of discharges travel means more particles will get affected per discharge. A denser rock means more mass can be accommodated in the treatment zone and therefore denser rocks should yield a larger portion of the sample in the product size fraction than expected, with the opposite being the case for low density rocks. It should be noted that the size and shape of the treatment zone depends on the electrode geometry. Therefore, the reported relationship is to some extent specific to the tip-plate electrode setup in the SELFRAG Lab unit. However, the relationship to tensile strength is likely to be a generic one irrespective of electrode design. The observed variation between rock types should be related solely to density (i.e. volume of material in the treatment zone) if the electrode geometry was the only factor of influence on particle breakage in the >14 mm fraction, but the correlation between density and decrease of mass in the feed size fraction is neither strong nor significant ( $r^2 \approx 0.02$ , sig. 0.61).

When plotting product size evolution with spark energy (represented through the slope of the power law) versus rock properties, it was found that acoustic impedance, Young's modulus, porosity and quartz content return good correlations to breakage. Density, point load index, compressive strength, tensile strength, and characteristic grain size did not show any significant correlation to the product size evolution with energy input ( $r^2 < 0.50$ ).

The best fit model for acoustic impedance versus breakage, shown in Fig. 14, is through a linear model ( $r^2 \approx 0.74$ ,

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#### Table 4

Mineralogical properties of tested rock types, including standard deviations.

	Porosity (%)	Weighted average grain size (µm)	Quartz content (mass%)	Sulphide content (mass%)	Carbonate content (mass%)	Mica content (mass%)
Altered metagabbro	<0.01	134	0.3	<0.1	.1	11.3
Andesite	$0.13 \pm 0.08$	37 ± 6	16.1 ± 5.7	$4.8 \pm 3.0$	$0.4 \pm 0.3$	31.9 ± 9.1
Chert	<0.01	54	47.6	1.08	<0.1	17.2
Dolerite	<0.01	39	13.1	<0.1	7.9	49.9
Gneiss	0.17	101	<0.1	<0.1	<0.1	$5.4 \pm 1.9$
Granite (fine-grained)	$0.08 \pm 0.02$	140 ± 5	32.0 ± 1.2	<0.1	<0.1	9.5 ± 0.3
Granite (medium- grained)	$0.42 \pm 0.56$	248.4 ± 75	31.4 ± 7.1	0.1 ± 0.03	<0.1	12.5 ± 3.1
Granite (porphyritic)	$0.12 \pm 0.04$	264 ± 56	35.0 ± 5.7	<0.1	<0.1	$12.3 \pm 0.1$
Granodiorite*	$0.47 \pm 0.60$	94 ± 25	27.3 ± 3.9	$1.8 \pm 0.5$	$4.5 \pm 0.1$	9.2 ± 1.9
Hornfels	<0.01	39	0.6	<0.1	<0.1	29.5
Limestone	0.26	n/a	<0.1	<0.1	99.6	<0.1
Iron ore (BIF)	$7.42 \pm 1.06$	n/a	n/a	n/a	n/a	n/a
Metagabbro	<0.01	154	<0.1	<0.1	<0.1	11.1
Pegmatite***	n/a	n/a	80.6	<0.1	0.1	0.9
Quartz monzodiorite*	<0.01	84	6.0	4.9	27.6	21.2
Sandstone	6.31	103 ± 3	$60.4 \pm 1.7$	<0.1	6.4 ± < 0.1	$4.6 \pm 0.6$
Shale/massive sulphide <sup>*</sup>	0.59 ± 0.22	305 ± 347	37.0 ± 25.4	$21.6 \pm 17.9$	29.5 ± 22.5	8.1 ± 7.2
Slate	0.107	23	15.4	0.3	1.6	46.1
Soapstone	0.55	48	<0.1	0.35	15.5	28.3
Tuff	<0.01	41 ± 1	15.6 ± 1.1	<0.1	6.1 ± 1.2	46.8 ± 1.3

\* Gold ore.

Copper ore.

Tantalum/Lithium ore.



**Fig. 13.** Slope of the exponential decrease of mass in the feed size (>14 mm) fraction as a function of tensile strength. Error bars indicate 95% confidence interval.

sig. < 0.001). There is a strong co-linearity between Young's modulus and acoustic impedance through Hooke's Law ( $E = \rho C_0^{-2}$ ). The correlation to Young's Modulus ( $r^2 \approx 0.70$ , sig. < 0.001) is not as strong as that found for acoustic impedance and therefore it is probably a consequence of the strong influence of acoustic impedance. A low acoustic impedance means a rock is less efficient at transferring shock wave energy, and hence more energy is absorbed during the wave transmission process, so the increased size reduction observed in low acoustic impedance rocks is a logical finding.

The relation between tensile strength and the disappearance of particles from the feed size fraction provides experimental evidence for the hypothesis by Bluhm et al. (2000) that fragmentation occurs in a tensile stress regime. However, the evolution of product

Fig. 14. Slope of the product size-energy relationship as a function of acoustic impedance. Error bars indicate 95% confidence interval.

particle size distribution with energy does not correlate well to tensile strength ( $r^2 \approx 0.22$  sig. 0.05). Micro-cracking of rocks is known to occur during high voltage breakage (Wang et al. 2011). This may significantly reduce the tensile strength of a rock, and could explain why the correlation between tensile strength and product size is not as significant. The correlation between product size and acoustic impedance provides experimental evidence for the suggestion that shock wave transmission is a major contributor to fragmentation during high voltage breakage. This fits in well with the relation to tensile strength as shock wave reflection and refraction within inclusions of different acoustic impedance would give rise to localised tensile stress.

The correlation coefficient between porosity and breakage is fairly low (0.42) but highly significant (0.005). Porosity is thought



Fig. 15. Slope of the product size–energy relationship as a function of Bond Work Index (closing screen size = 355  $\mu m$ ).

to be of importance because the two major outliers in Fig. 14 (sandstone and iron ore), have the highest porosities (5.62% and 6.36% respectively) of all rock types tested (average porosity 0.22% for the rest of the data set). This may be related to the lower electrical breakdown strength of air, which invariably is lower than that of water and rocks regardless of pulse rise time and voltage (Andres et al., 2001b). Air trapped in pores may therefore be more facilitating to electrical breakdown and the formation of a plasma channel, resulting in more efficient breakage. Further investigation of this effect is recommended due to the relatively limited distribution of porosity (0.001-0.5% when excluding the two outliers) for the available rock types. Though permeability was not considered in this research, it may also be of influence on breakage by allowing treatment water to percolate into voids occupied by prior to high voltage treatment. This could to some extent negate the positive effect of porosity on the ease of fragmentation during high voltage breakage.

The quartz content appears to be related to breakage through a linear relationship ( $r^2 \approx 0.54$ , sig.  $\approx 0.004$ ). Furthermore, the finest product sizes at any given treatment were observed for the rock types with the highest quartz content materials (pegmatite and sandstone). It is possible the influence of quartz content is related to piezo-electric behaviour (i.e. charge accumulation in response to mechanical stress) of quartz, or its brittle nature but no conclusive explanation is yet available. Co-linearity of porosity and quartz content with other properties such as acoustic impedance is not strong enough to explain the influence of these properties.

No correlation could be established between measured rock properties and the minimum voltage gradient required for breakdown. Likewise, the rock-specific variation in generator to spark energy conversion could not be explained by any known rock properties. As both are related to electrical characteristics of high voltage treatment they are more likely linked to electrical properties and these values were not available in this research. Further work is underway to determine interaction between high voltage processing and the electrical properties of the rock being processed.

The correlation between Bond Work Index and the evolution of product size with energy input (Fig. 15) is significant and strong ( $r^2 \approx 0.89$ , sig. < 0.001), but heavily reliant on the sandstone outlier ( $r^2 \approx 0.20$ , sig.  $\approx 0.11$  when sandstone is excluded). Therefore, Bond Work Index may serve as a very rough indicator of ease of breakage during high voltage treatment, which may prove useful given the fact that a Work Index is determined for practically every ore being comminuted. At the same time though, it should be pointed out that the variation in Bond Work Index between sam-

ples is far larger than that observed in ease of breakage by high voltage discharges. A good example is the hornfels producing nearly exactly the same product size as the limestone, despite having a Bond Work Index almost twice as high (17.1 vs. 9.0 kW h t<sup>-1</sup>). Implications of these observations will be discussed further in the following section.

#### 4. Relevance of findings to a continuous process

Continuous high voltage breakage equipment for weakening of ores should have two primary goals: (1) to achieve an optimal balance between energy introduced into an ore and reduction in energy requirements due to high-voltage induced weakening of ores, and (2) to apply the pulsed energy in the most efficient manner.

The data presented in this paper show fragmentation behaviour is rock-specific. Figs. 5, 6 and 8 show that high voltage energy inputs generally are too high to make it a feasible technology for full fragmentation unless the improved liberation (and potentially better grade/recovery), such as that reported by Wang et al. (2012) can be used to justify the higher energy input. Individual assessment per rock type will be required to determine where the optimal trade-off is between reduced energy demand after weakening and high voltage energy spent in achieving this weakening. Research by Wang et al. (2011), and initial research results available at the Camborne School of Mines suggest that a significant reduction in energy requirements after weakening can be achieved at energy inputs of approximately 2–5 kW h t<sup>-1</sup> of spark energy.

On the basis of presented data it is impossible to pin-point a particular combination of voltage and total number of pulses to achieve an optimal trade-off between weakening and high voltage energy input. However, the data do show conclusively that the electrode gap at a pre-selected voltage (i.e. the voltage gradient) should be high enough to exceed the threshold value where the discharge ratio as high as possible (i.e. >0.95). Results suggest 7 kV mm<sup>-1</sup> should be sufficient, regardless of other variables such as process water conductivity. At the same time, electrode gap also influences throughput by determining the volume available between electrodes, and hence the top size of particles that can be treated. This means a compromise has to be considered when increasing the voltage gradient at the expense of top size treated. Individual assessment of the most suitable feed size, voltage and electrode gap for a rock type is likely needed to determine ideal settings. Because this entire publication is based on data from a small scale batch process, it is strongly recommended that selected experiments are reproduced on a larger scale or in a locked-cycle test to determine unit performance in a continuous processing environment, especially with regards to energy utilisation.

A higher pulse rate means the same amount of energy can be applied in a shorter period of time, and hence the residence time of particles in the treatment area can be reduced. At the same time it also increases the likelihood of a pulse developing a discharge so for efficiency purposes it is recommended the pulse rate is maintained as high as possible.

With regards to rock mass properties, it appears rock types with any combination of low acoustic impedance, high porosity and high quartz content are most amenable to high voltage breakage. It is recommended these materials are targeted for high voltage breakage experiments. If rock cores are available (i.e. diamond drill core on an exploration project), acoustic impedance can be determined in a time and cost effective manner using precision scales, a vernier calliper and an acoustic tester. The presence of silica in a large number of common rock-forming minerals makes accurate determination of quartz content through chemistry complicated.

Typically, point counting, quantitative X-Ray Diffractometry or quantitative automated mineralogy (i.e. QEMSCAN or MLA analysis) would be required. However, provided the rock is not too fine-grained, quartz is easily recognised in lump material and an empirical visual assessment ( $\pm$ 5%) may suffice. A similar situation applies for porosity. Measurement of porosity by QEMSCAN can be considered qualitative to semi-quantitative in nature and accurate determination requires mercury porosimetry, which is a costly procedure. Initial results suggest porosity levels <1.00% are of little consideration to high voltage breakage.

A high comminution energy input after high voltage treatment means it is more likely that weakening will off-set the additional high voltage energy input to result in a net reduction in overall energy demand. Furthermore, the correlation between high voltage breakage and Bond Work Index is limited (see Fig. 15). Therefore, processing circuits treating harder materials or grinding material to a comparatively small passing size should offer more scope for potential energy saving after high voltage-induced weakening. Combining this consideration with the effect of feed size on high voltage breakage, it is suggested that high voltage breakage is best implemented in a circuit processing an ore with a high Work Index, treating relatively coarse (>20 mm) material (i.e. pre-SAG mill, or possibly pre-ball mill if the feed is coarse enough). The top feed size for high voltage breakage depends on the electrode geometry, and the top-end of the feed size effect. It is also suggested finer material (<10 mm) is removed as these feed sizes may consume part of the spark energy without undergoing significant weakening. These suggestion are based on the feed size effect and the assumption that earlier implementation of high voltage breakage in a process offers more scope for energy reduction through weakening, and need further investigation to ascertain where potential benefits from high voltage breakage can be realised most fully.

### 5. Conclusions

The purpose of this research was to establish what influence equipment settings, feed size and rock properties have on fragmentation behaviour during high voltage breakage. Key conclusions drawn from the data and considerations presented in this paper are:

- Rocks being fragmented using high-voltage breakage equipment all experience an initial phase at low energy inputs (<5 kW h t<sup>-1</sup>) during which little size reduction occurs, followed by a strong decrease in size levelling off towards high energy inputs.
- Total applied energy is the main variable to be considered for product size (controlled through both number of discharges and voltage).
- The applied voltage controls the amount of energy deposited per discharge. For the majority of rock types the influence of voltage on the product size does not deviate from the general energy-product size relationship for a rock, but some rocks display a 'threshold voltage' below which fragmentation is less effective.
- Voltage gradient between electrodes can be influenced through voltage and electrode gap. A minimum voltage gradient (approximately 7 kV mm<sup>-1</sup>) needs to exist to reliably achieve discharges.
- Pulse rate can be increased to improve the probability of a discharge occurring.
- There is a strong feed size effect, with coarse particles being considerably more amenable to high voltage breakage than fine particles.

- The amount of particles in the feed-size fraction after treatment decreases exponentially with energy input. The rate of decrease can be correlated to tensile strength, suggesting fragmentation occurs in a tensile stress regime.
- Acoustic impedance shows a significant correlation to product size, providing experimental evidence for shockwaves playing an important role in high voltage breakage.
- Porosity and quartz content are two other rock properties that can be linked to breakage behaviour. Bond Work Index does not show a robust correlation to high voltage breakage, but may be used as a first-order indication of ease of breakage.
- High voltage breakage would be best implemented prior to grinding.

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