POTENTIAL APPLICATIONS OF ORE PRE-CONCENTRATION USING HIGH VOLTAGE PULSES FOR AG/SAG MILLING

*Fengnian Shi, Weiran Zuo, and Emmy Manlapig

The University of Queensland, Sustainable Minerals Institute,
Julius Kruttschnitt Mineral Research Centre,
40 Isles Road,
Indooroopilly, Brisbane, Qld 4068, Australia
*(*Corresponding author: f.shi@uq.edu.au)*

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ABSTRACT

A novel technique using high voltage pulses (HVP) for ore pre-concentration has recently been reported. The technique utilises metalliferous grain-induced selective breakage and size-based screening to separate the feed ore by grade. Four copper-gold ore samples were tested to demonstrate the viability of this technique. Potential applications of the HVP pre-concentration technique to treat AG/SAG mill pebbles and AG/SAG mill feed are discussed. An HVP ore pre-concentration characterisation diagram is proposed to assess the performance of a given ore. This technique may have the potential for the mining industry to make a step-change in improving comminution efficiency and separation recovery.

KEYWORDS

High voltage pulses, Electrical comminution, Ore upgrading, Pre-concentration

INTRODUCTION

Coarse waste rejection has the potential to pre-concentrate valuable minerals before or during AG/SAG milling. The upgraded AG/SAG feed can bring benefits of reduced milling throughput to achieve the required metal production, reduced energy consumption and improved comminution and recovery efficiency. This will help the mining and minerals industry to make a step-change in reduction of the energy input per unit of final product (Bearman, 2013).

Implementation of coarse waste rejection is dependent on the geological setting and association of ore and host rock type in a deposit. In some processing plants, the Run-of-Mine (RoM) ore exhibits a size-related grade differentiation between the value hosting rock particles and barren material. Burns and Grimes (1986) reported pre-concentration of a copper ore by screening at the Bougainville copper plant operation. Based on detailed recovery-size-yield data collected from the Newcrest Telfer operation, Bowman and Bearman (2014) reported a potential application of coarse waste rejection through size-based separation for copper production. It was found that rock strength may sometimes associate with metal grade. Modifications to the energy intensity delivered to various areas of the blast can also be implemented to induce the size-related grade differentiation for coarse waste rejection (Powell & Bye, 2009).

Despite the simplicity of a separation system using a conventional screen to achieve size-related grade splits, the success of coarse waste rejection is largely dependent on the accurate classification into a dedicated ore database. There is no doubt that ore variation will affect the waste rejection efficiency and the value loss, since the grade of the coarse waste component in the feed is not directly measured by an on-line grade measuring system before being rejected.

In the past few years, high voltage pulse (HVP) technology has been explored for the potential applications of ore pre-weakening (Razavian, Rezai, & Irannajad, 2014; Shi, Krishnan, von der Weid, van der Wielen, Zuo, & Manlapig, 2014a; Shi, Zuo, & Manlapig, 2013; Usov & Tsukerman, 2006; van der Wielen, Pascoe, Weh, Wall, & Rollinson, 2013; Wang, Shi, & Manlapig, 2011) and mineral liberation (Andres, 1977, 1995; Andres, Timoshkin, Jirestig, & Stallknecht, 2001; Cabri, Rudashevsky, Rudashevsky, & Gorkovetz, 2008; Ito et al., 2006; Lastra & Cabri, 2003; Parker, Shi, Evans, & Powell, 2015; Wang, Shi, & Manlapig, 2012). Recently, the Julius Kruttschnitt Mineral Research Centre (JKMRC) reports a new application of HVP technology for ore pre-concentration (Shi, Zuo, & Manlapig, 2015; Zuo, Shi, &

Manlapig, 2015). This paper discusses the potential applications of HVP ore pre-concentration for AG/SAG milling.

ORE GRADE-SPLITTING BY HIGH VOLTAGE PULSES

HVP breakage is a comminution method that uses high voltage pulses (over 100 kV) to initiate electrical breakdown inside an ore particle, generating a strong tensile force to disintegrate the particle. When the HVP treatment took place in a single-particle, single pulse mode (Shi et al., 2013), it was observed that some particles were broken into several fragments and some only lost a few chips from particle edges. The former breakage pattern was classified as body breakage and the latter as surface breakage (lost less than 10% of the initial particle mass).

An experiment using synthetic particle samples was conducted to study breakage behaviour under HVP loading. Synthetic samples were made using high strength grout comprising quartz sand in a narrow size fraction around 300 µm and cement powder. The diameter and height of the synthetic particles were 38 mm and 30 mm respectively. A single pyrite grain of 2.36-3.35 mm was embedded in some of the synthetic particles immediately after the casting of paste. The volume of pyrite grain took up less than 0.07% of the whole synthetic particle. Each of the synthetic particles was subjected to a controlled low specific energy (less than 2 kWh t^{-1}) using a selFrag Lab machine installed at the JKMRC. The synthetic particles with pyrite grain embedded in their centre attracted electrical breakdown channels which passed through the boundary of the pyrite grain, causing a radial explosion from the particle centre. All the synthetic particles with a single grain of pyrite embedded in the centre were broken explosively by one high voltage pulse. By contrast, at the same pulse treatment conditions, only 43% of the synthetic particles without pyrite were broken by the first pulse.

Further study was carried out using four copper-gold ore samples collected from SAG mill circuits in various Australian mining operations. Five tests on the four ore samples in narrow size fractions were conducted using the single-particle, single-pulse breakage method. Table 1 presents the copper results and Table 2 the gold results from the five tests. Tests 1 and 2 were duplicate tests for Ore sample A. Approximately 30 particles in each test were treated by HVP. The pulse-treated particle was inspected and classified into the body breakage or surface breakage product. Each product group was crushed and ground for assays by XRF. The gold assay was performed using ICP.

Tables 1 and 2 demonstrate that there are significant differences in copper and gold grades between the body breakage product and the surface breakage product. The data confirm the ore grade-splitting function of HVP. The mass yield of body breakage product depends on ore properties and the HVP operational conditions. In Test 5 using Ore sample D, 26.5% of the feed particles reported to the body breakage product and 73.5% to the surface breakage product when subjected to 1.3 kWh t^{-1} specific energy. The surface breakage product contained 0.028% Cu and 0.005 ppm Au. The gold grade of the surface breakage product is lower than the tailing grade in the current operation.

Tests 1 and 2 were duplicate tests on the same ore source conducted half a year apart. The mass yield was very similar (61.4% versus 60.9% reported to the body breakage product) in the two tests. The surface breakage product grades were also very similar (0.109% Cu versus 0.104% Cu in Table 1 and 0.22 ppm Au versus 0.206 ppm Au in Table 2). The grade differences in the body breakage products between the duplicate tests (0.244% Cu versus 0.186% Cu in Table 1 and 1.88 ppm Au versus 0.535 ppm Au in Table 2) were larger than that in the surface breakage product. The duplicate tests indicated that at the given pulse energy input settings and the operational conditions, the cut-off metal contents (i.e. the copper grade or the gold grade in the "unbroken" product) and the mass split between the 'broken' and "unbroken" components were consistent. The differences in the body breakage product grades were attributed to the variation in the copper and gold contents in each particle in the body breakage product, which can be mitigated by adequate sampling protocols.

Table 1 – Mass yield and copper grade-splitting in body breakage and surface breakage products

Test	Feed	Pulse	Body breakage product			Surface breakage product		
	(mm)	(kWh t^{-1})	Mass (%)	Grade (%Cu)	Cu Dist. (%)	Mass (%)	Grade (%Cu)	Cu Dist. (%)
1	26.5-31.5	3.7	61.4	0.244	78.1	38.6	0.109	21.9
2	26.5-31.5	3.9	60.9	0.186	73.6	39.1	0.104	26.4
3	31.5-37.5	2.3	32.1	0.306	44.5	67.9	0.181	55.5
4	37.5-45.0	1.4	60.5	0.386	83.8	39.5	0.114	16.2
5	31.5-37.5	1.3	26.5	0.102	57.1	73.5	0.028	42.9

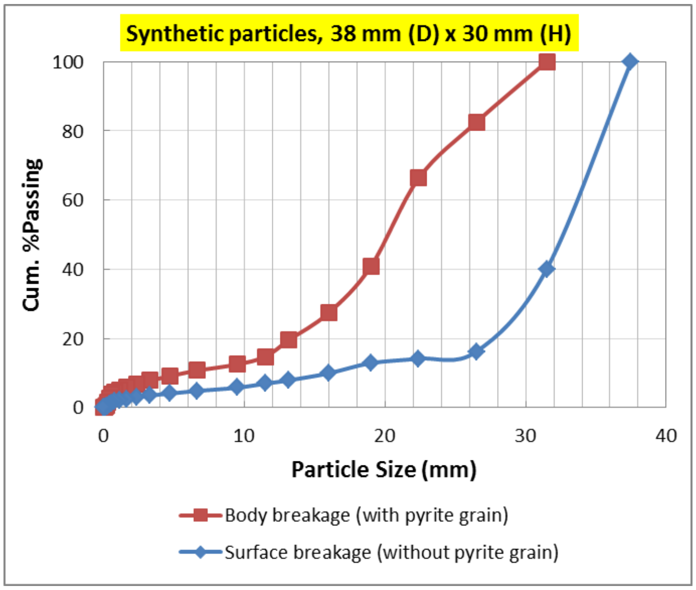
Table 2 – Mass yield and gold grade-splitting in body breakage and surface breakage products

Test	Feed	Pulse	Body breakage product			Surface breakage product		
	(mm)	(kWh t^{-1})	Mass (%)	Au grade (ppm)	Au Dist. (%)	Mass (%)	Au grade (ppm)	Au Dist. (%)
1	26.5-31.5	3.7	61.4	1.880	93.2	38.6	0.220	6.8
2	26.5-31.5	3.9	60.9	0.535	80.2	39.1	0.206	19.8
3	31.5-37.5	2.3	32.1	2.280	61.5	67.9	0.670	38.5
4	37.5-45.0	1.4	60.5	0.991	86.3	39.5	0.242	13.7
5	31.5-37.5	1.3	26.5	0.397	96.6	73.5	0.005	3.4

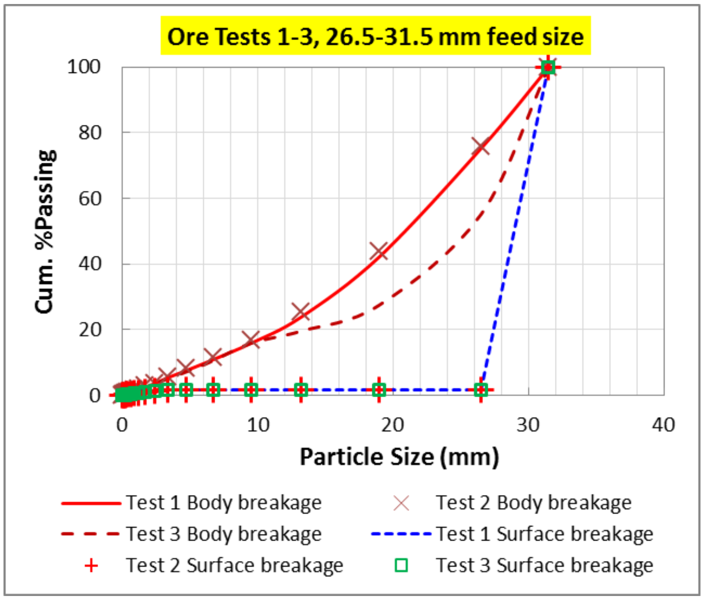
CONCEPTUAL DESIGN FOR HVP ORE PRE-CONCENTRATION

In the HVP ore grade-splitting experiment, the HVP treated particles were classified into the body breakage and surface breakage products. This was done by manual inspection of each particle based on whether or not the treated particle lost more than 10% of its initial mass. To achieve ore splitting by grade for the mineral industry, it is necessary to separate the HVP treated particles into two groups automatically and continuously.

It was observed that there were significant differences in size distributions between the body breakage and the surface breakage products. Figure 1 shows the HVP product size distribution curves for the synthetic particles (Figure 1a) and the Ore sample A (Figure 1b). Figure 1a illustrates that at a screen cut size of 30 mm, 95% of the body breakage fragments (containing pyrite grain) in the synthetic samples will report to the screen undersize product, and 70% of the surface breakage particles (without pyrite) will report to the screen oversize product. Similarly in Figure 1b for Ore sample A, at a screen cut size of 26.5 mm (ie. the bottom sieve size of the feed) 75% of the body breakage fragments will report to the screen undersize product, and 98% of the surface breakage particles to the screen oversize product for Tests 1 and 2. As shown in Tables 1 and 2, there are significant differences in copper and gold grades between the body breakage and the surface breakage products. Therefore the size-based separation can achieve the expected grade-splitting for the HVP treated ore particles. Figure 1b also demonstrates good repeatability of the HVP treated product size distributions.



a. Synthetic samples



b. Ore sample A

Figure 1 – Comparison of size distributions between the body breakage and the surface breakage products, 30 particles for each group, each particle subjected to one pulse loading

A conceptual design of ore grade-splitting by HVP was developed (Zuo et al., 2015). As illustrated in Figure 2, the design utilises metalliferous grain-induced selective breakage, under a controlled pulse energy loading, and size-based screening to separate the feed ore into body breakage and surface breakage products for splitting of ores by grade. A Proof-of-Concept (PoC) of an integrated system implementing the principle presented in Figure 2 will resolve the issues of scaling-up for industrial applications. To build such a PoC unit requires collaboration by researchers, high voltage pulse supplier, equipment manufacturer and the mining industry.

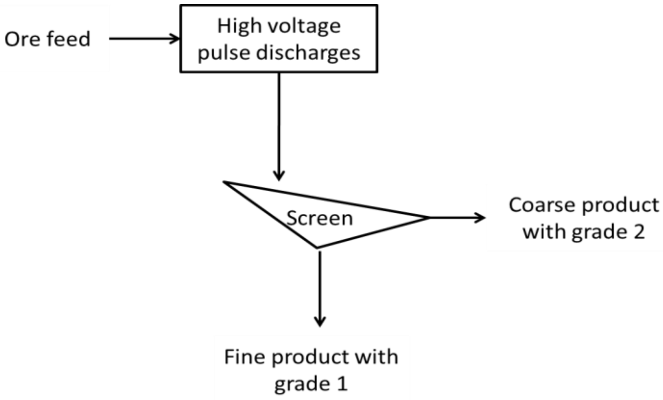


Figure 2 – Process of ore pre-concentration by high voltage pulse breakage (Zuo et al., 2015)

POTENTIAL APPLICATIONS IN AG/SAG MILLING CIRCUIT

A number of applications of the HVP pre-concentration technology for the mining industry have been discussed by Shi et al. (2015). In the present paper, the following two applications in an AG/SAG milling circuit are further discussed.

AG/SAG Pebble Treatment

In an AG/SAG mill operation, some competent rocks with an approximate size range of 20-75 mm that are too small to be used as grinding media for the breakage of other particles but too large to be broken by grinding media, are often discharged through pebble ports at the mill discharge end. It is well known that part of the pebbles may be barren rocks; but there was no suitable technique to identify and separate these barren rocks before returning them back to the AG/SAG mill (with or without pebble crusher). Pebble treatment is a critical issue in AG/SAG operation, as they reduce mill capacity and increase mill energy consumption.

The HVP pre-concentration technology can be employed for pebble treatment. In this application, each pebble particle is subjected to a controlled pulse energy loading, which is just sufficient to detect the existence of the metalliferous grains inside the particle and fracture the particle by the metalliferous grain-induced breakdown channel. If the particle is a barren rock containing no metalliferous grains, the particle is unlikely to be broken by being subjected to the same pulse energy. As a result, the electrical pulses treated pebbles will show a difference in product size. The intact pebbles will remain on a screen with the selected apertures and will be rejected prior to re-entering the AG/SAG mill. The broken pebbles will report to screen undersize and be returned to the mill for further grinding. Figure 3 shows an example of pebbles from a copper ore SAG milling circuit, which was treated by HVP using a selFrag Lab installed at the JKMRC. The pulse treated pebbles were classified into body breakage and surface breakage products. XRF assays indicated a significant difference in copper grade between the two products. Before the treatment, it was unable to distinguish the pebble particle grade by human eyes. Approximately 27% by mass of the pebbles can be rejected with a grade of 0.07% copper. In comparison, the returned pebbles have a grade of 0.28% copper, representing 91.5% metal recovery in the HVP pre-concentration process.

Figure 3 – SAG mill pebbles (31.5-37.5 mm) treated by high voltage pulses and separated into two groups for assay

AG/SAG Feed Treatment

The concept of HVP pre-weakening AG/SAG mill feed has been discussed (Wang et al., 2011) and the simulation study implementing the pre-weakening concept for various hybrid comminution circuits has been reported (Shi et al., 2014a). The new application of HVP pre-concentration of AG/SAG mill feed can be combined with the pre-weakening application to realise a more significant benefit.

In the proposed HVP pre-concentration application, the AG/SAG mill feed ore is divided into six size fractions: +150 mm, 100-150 mm, 50-100 mm, 25-50 mm, 9.5-25 mm and -9.5 mm. The +150 mm ore can be treated by HVP; but in an AG application it is better to reserve the +150 mm ore, which will be used as the grinding media. The -9.5 mm fine particles will go directly to the AG/SAG mill, as the efficiency of HVP is reduced rapidly for sub-ten mm particles. The other four size fractions will be treated by the HVP pre-concentration facilities. The HVP product of each feed size fraction will be screened to differentiate the body breakage and surface breakage particles. The screen undersize materials will be combined with the untreated +150 mm and the -9.5 mm from the RoM feed and sent to the AG/SAG mill.

Depending on the ore pre-concentration characteristics and the HVP operational settings, the low grade HVP product may mainly contain rocks with tailing-like grade. The barren rocks can be rejected before entering the AG/SAG mill. Reduced energy consumption per ton of metal production or increased milling capacity can be expected by rejecting these barren rocks.

Alternatively, the HVP treatment can split the RoM ore into multi-components of grade by incremental pulse loading. Different metal recovery methods may be applied to the different grade ores. For example, the high grade ore with small mass yield may be treated by comminution followed by flotation, and the low grade ore treated with leaching without comminution. The high grade ore may be associated with coarser grain size, which offers the benefits of coarse grinding for energy saving. For the low grade ore used in the leaching process, the cracks/microcracks generated in the HVP treatment will provide passages for the reagents to contact the valuable minerals. Improved leaching recovery can be expected.

ORE PRE-CONCENTRATION CHARACTERISATION

The HVP pre-concentration results reported here were all from copper-gold ores, potentially the technique may be used for other minerals. It is understood that variations in particle mineralogy, texture, distributions of metalliferous minerals in relation to rock-forming minerals in a particle, interactions among various metalliferous minerals, mechanical breakage properties, etc. will affect the HVP pre-concentration results. Ore pre-concentration characterisation is therefore essential to determine the response of a given ore, or a given orebody, to the HVP treatment. Ore pre-concentration characterisation consists of two major aspects:

- Phenomenal determination: This is to quantitatively establish relationships between HVP input energy, mass yield, two product grades and recoveries for the ore samples provided by the mining companies.
- Fundamental study: This is to understand the ore response to the HVP treatment, using advanced measurement technology, and to optimize the HVP treatment conditions.

Figure 4 presents an HVP pre-concentration characterisation graph for a copper ore in a given size fraction, using the real experimental data (Shi et al., 2015). There are four response curves in the characterisation graph. Given one point on the graph, the corresponding values for the other three variables can be found from the characteristic curves. By way of example, if the pre-concentration operation is required to recover 85% of copper to a high grade circuit, the Cu grade for screen undersize and screen oversize are 0.59% and 0.14% respectively, the mass yield to the screen undersize is 58%, and the required specific pulse energy is 2.6 kWh t^{-1}.

The HVP pre-concentration graph provides a theoretical performance guideline for the given ore sample. The theoretical performance data can be used to evaluate the viability of the HVP pre-concentration technique, to design a comminution and separation circuit, to assess economic benefits, and to assist in justifying an investment decision.

In the fundamental study, X-ray computed tomography (X-ray CT) is a useful tool for the pre-concentration mechanism study. The JKMRC has installed a Versa 500 X-ray tomography device. CT is a technology that uses computer-processed X-rays to produce tomographic images of specific areas of the scanned object. High-resolution imaging data on particle sizes up to 50 mm can be generated with high speed. The imaging data provide 3D information about mineral grains, their size, shapes and locations in the environment with the gangue minerals surrounding them. Since X-ray CT can “see through” the particles and provide 3D information, this technical tool will help understand the selective breakage mechanisms in the HVP pre-concentration process. Other mineralogical analysis instruments installed at the JKMRC such as MLA, XRF and XRD will offer useful tools in providing information on mineralogy, metal distribution, metalliferous grain size distributions, etc. The JK Rotary Breakage Tester (JKRBT, Shi, Kojovic, Larbi-Bram & Manlapig, 2009) will be used to determine the HVP pre-weakening effect, the JK Fine-particle Breakage Characteriser (JKFBC, Shi & Zuo, 2014) will be used to measure grindability of single mineral component produced in the HVP treatment.

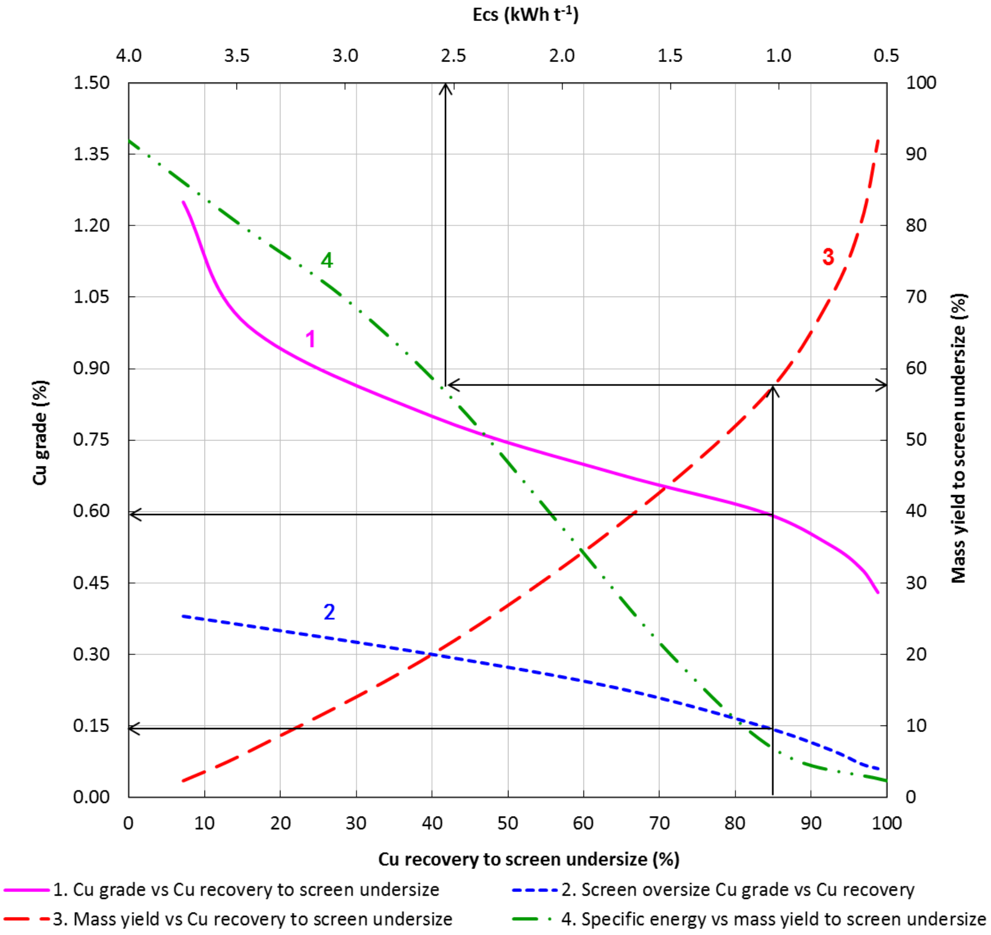


Figure 4 ─ The proposed electrical pulse pre-concentration characterisation curves (Shi et al., 2015)

CONCLUSION

This paper introduces a novel technique that uses high voltage pulses to selectively break particles containing metalliferous minerals, and then a size-based screening procedure to split the ore by grade. Four copper-gold ore samples were tested to demonstrate the viability of this technique. The XRF data show clear evidence of the differences in the copper and gold grades between the body breakage and surface breakage products treated by HVP.

The discovery of the HVP pre-concentration technique provides a new tool for the mineral industry. Potential applications of this technique to treat AG/SAG mill pebbles and AG/SAG mill feed are proposed. Due to ore variation in mineralogy, texture, grain size, metalliferous minerals interaction, mechanical breakage properties, etc., it is essential to quantitatively determine the response of a given ore or a given orebody to the HVP pre-concentration technique. A new HVP ore pre-concentration characterisation diagram is suggested to evaluate the viability of the technique to the ores of interest by the mining company. Fundamental study is necessary to understand the mechanisms of HVP selective breakage and to optimise the HVP pre-concentration performance. This technique has the potential for the mining industry to make a step-change in improving comminution efficiency and separation recovery.

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