Rethinking breakage for mineral recovery

Malcolm S Powell[1,2]

[1]Liner Design Services, Fig Tree Pocket, 4069, Australia
[2] SMI-JKMRC, University of Queensland, Brisbane, Australia

Abstract. Many measures of breakage used in mineral processing are defined for conventional equipment and do not reflect the fundamentals of particle fracture or the purpose of the breakage. Simplistic single-point size indicators and laboratory breakage energy tests with low efficiency drive a backward-looking view of technology and risk.

Reassessing a target breakage size distribution related to mineral exposure and recovery routes, provides a new perspective on process efficiency. This enables redefinition of the ideal product size as a function of ore feed type and recovery processes, including staged recovery. The overall process efficiency can be assessed not only in terms of tons of metal produced but critically based on energy (including green energy), recovery, water use, and tailings production.

Utilising these fresh insights combined with the objectives of size reduction in mineral processing, has inspired a rethinking of the measures of breakage that can usefully be applied.

1 Introduction

Within mineral processing, the purpose of comminution is to expose minerals for separation from the gangue and other minerals, which themselves may be valuable or deleterious. Depending on the recovery process, the required form of exposure varies:

- Flotation: sufficient surface exposure for activation and bubble attachment.
- Leaching: access to the minerals on the surface or via cracks or porosity.
- Physical separation (e.g., gravity, electrostatic, or magnetic): sufficient volume fraction in a particle to differentiate from the barren particles.
- Sorting: detectible volume fraction within a particle.

Consequently, these have different breakage objectives. The common metric of product size to suit any process is the P80 value, a convenient single-point measure that can be quoted across projects. The cost and efficiency of different comminution process options to achieve this P80 may be used in trade-off studies to choose an optimal process over the life-of-mine. The problem is that this can be misleading, as different processes produce different size distributions and present quite different opportunities, or lack thereof, for staged upgrade of the minerals.

There is considerable value to updating the accepted simplistic practice of single-point size description, instead relating the product size to purpose.

2 Size distribution and recovery

The size distribution of comminuted product depends on the types of equipment used, as illustrated in Figure 1. Which shows product streams sampled along stages of a single comminution circuit, from run-of-mine (RoM) feed through stages of crushing and milling to the final cyclone overflow product. The product size distribution from a unit process is a function of the breakage modes, residence time, classifier, and method of operation.

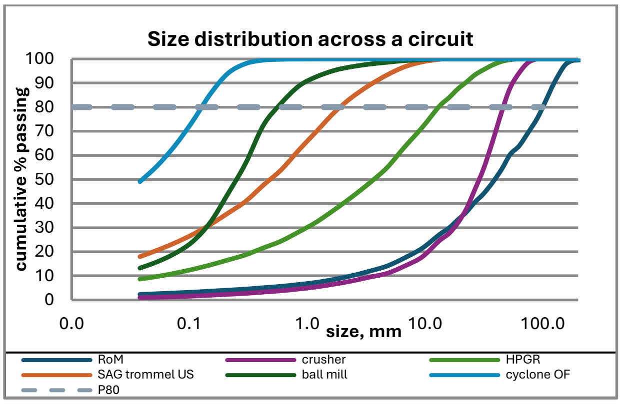

Figure 1 Different size distributions across a single circuit [9]

Infamously, ball milling was incorrectly considered to be more efficient than SAG milling as the operating work index was calculated to be lower based on the simple P80 values required by the Bond equation [5]. To address this, models compensating for the larger proportion of fines produced by the SAG mill, have been developed by investigators such as Morrell [8].

Comminution units are imperfect, so the products are sent to a classifier to direct particles to the next stage or recycle to the equipment. Classification is dependent on size, density and shape of particles. The higher density of mineralised particles results in a different size distribution of the mineralised to barren particles. Hence, the type of classifier and degree of recycle contribute to the liberation profile of the comminution product [6].

However, the attraction of a single-point comparison remains strong and still pervades the mining industry when developing target grind sizes, that are not related to the upstream process.

A brief overview of different recovery processes focussed on feed size distribution provides context for the purpose of ore preparation.

Flotation

Mineral recovery by flotation dominates many commodities in the minerals industry. Considering the typical form of a flotation recovery-by-size curve presented in Figure 2, it drops off below a fine size due to non-selectivity, and above a coarse size due to non-liberation and particle size effects.

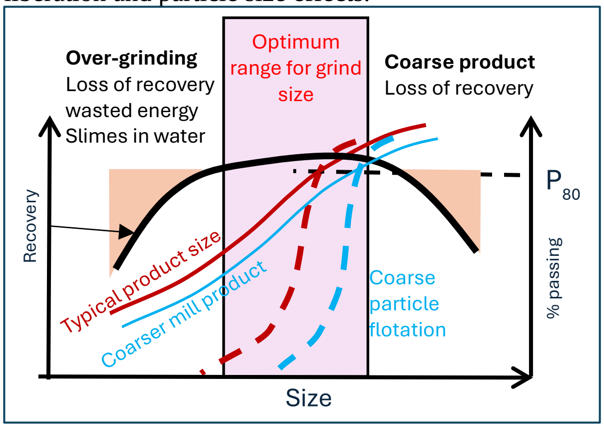

Figure 2 Recovery by size and feed size distributions

A typical product size distribution from a ball mill circuit is superimposed to illustrate that much of the product from the comminution circuit falls outside the optimum recovery size range. If a steeper size distribution can be produced with the same P80 as that of the ball mill circuit, shown by the dashed red line, more of the particles will fall within the optimum recovery range. For a coarse particle recovery system, the product can be coarsened further (blue dashed line) while still providing optimum recovery.

In a typical process specification, the two comminution processes with identical P80's would be considered identical in performance. However, the shape of the feed recovery size distribution has a significant impact on the recovery potential. Additionally, simplified energy calculations based on size P80 reduction relationships, may ignore the considerable energy reduction due to the steeper comminution product, where energy is not wasted on producing unwanted fines.

Coarse particle recovery offers the considerable advantage of reduced comminution energy, easily calculated by a coarser product P80. However, the ideal dashed blue line is not achieved in milling equipment. Instead, the coarser mill product (blue line) inexorably retains a high fraction of fines, as this is intrinsic to the SAG-ball milling and classification process.

Sorting

Particle-based sorting involves direct measurement of particle properties, such as by XRF, transmission X-ray, or colour. Gangue particles are ejected, based on a cut-off grade, thereby upgrading the feed to the final recovery process. Like any selection system, the process has inherent inefficiencies described by a probability distribution by size for a given ore. The detection method, data processing, and physical ejection (usually air jets), limit the system to processing a relatively narrow effective range of particle sizes. To enable efficient sorting, the feed has to be screened to a suitable mid-size.

Figure 3 illustrates the principle of sorting recovery for a system that is efficient in the 10-25 mm range, overlaid on measured product streams around a HPGR, SAG, crushing, and pebble crushing products.

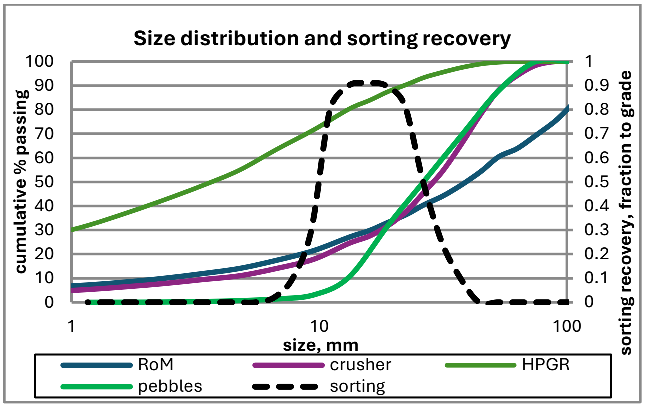

Figure 3 Overlap of sorting size range with product streams

All the streams have a limited fraction that can be sent to sorting:

- HPGR: 15%
- Crushed feed: 30%
- RoM feed: 20% (but expensive to screen)
- Pebble crusher: 50% x 20% of feed = 10%

As each of these conveyor streams is destined for a different part of the downstream process, this would entail multiple screening points, an expensive process. The underlying issue is that the feed is not conditioned to fall within the narrow size range required for efficient sorting.

Bulk ore sorting

Bulk sorting measures the average grade of a batch of rock. It is well suited to RoM feed on the main feed conveyor when ore properties are highly variable. Loss of grade is intrinsic to the approach, as decisions are made on parcels of ore. This is a low-cost sorting method, diverting rejected material out of the processing stream. The risk is that ores that show little spatial variability can lead to substantial losses of valuable material to the reject stream.

Heap leaching

Heap leaching allows recovery from low-grade feed streams that are not economic to process via the comminution and recovery circuit. Often this involves coarsely crushed ore which is stacked on the pad. Some sites partially screen or crush to better condition the size distribution for more consistent porosity and percolation of the lixiviant. Recovery is slow, typically over months, and can vary widely: often 50-70%, but significantly lower where permeability or mineral accessibility is poor. It is well understood that crushing, minimising fines, and careful distribution on the pad greatly enhance recovery, but at a substantial processing cost that often cannot be justified.

3 Shifting the paradigm

Having considered the link between particle size distribution and recovery, the potential inherent in designing the comminution process to enhance recovery can be considered.

Based on the liberation model of Hilden [7] fitted to a porphyry ore body, an upgrade curve has been compiled [3] as illustrated in Figure 4. This provides a smoothed mathematical description of the mass recovery for a range of sizes for a target metal recovery, i.e. the ore upgrade or removal of mass. For this data, to recover 95% of the metal from the RoM ore, on average 80% of the mass would need to be recovered. For the material crushed to sub-1 mm, only 15% of the ore mass needs to be recovered to recover 95% of the metal. Clearly this will change according to ore type and process but can be fitted to testwork for particular ores and recovery processes.

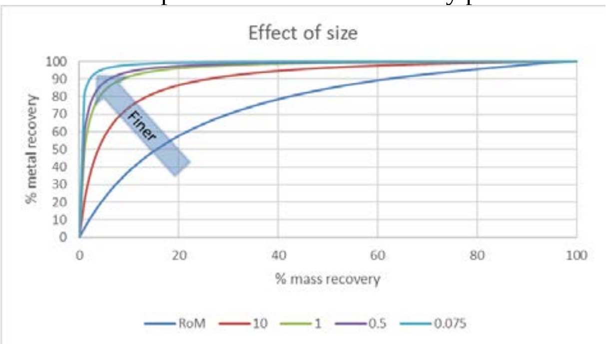

Figure 4 Recovery by mass for decreasing feed size [3]

Combining the energy usage figures with a metal recovery model, provides a method to calculate the overall relationship between energy used and total potential metal recovery. An analysis of the impact of removing 40% of the rock through a sorting or upgrade step at one of a number of size options is presented in Figure 5. All the values are relative to the standard process of milling the full feed to final size and the associated floatation recovery, both energy and recovery for the base case being 100% in these relative figures.

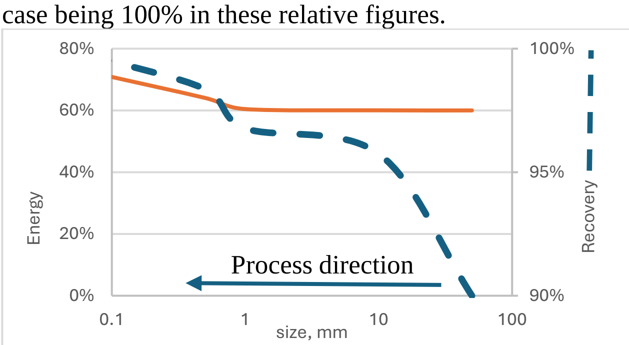

Figure 5 Relationship between metal recovery and energy usage for 40% mass removal at different sizes

If the upgrade is through coarse rejection ahead of comminution, then the energy consumption reduces to 60%, but with the penalty of recovery potential reducing to below 95% of current. The energy saved reduces as the 40% mass removal is conducted at finer sizes, with 70% energy usage at 0.1 mm upgrade size, but this provides a far superior 98% to 99% recovery. This shows there is a strong trade-off of recovery with upgrade size.

Figure 6 shows the outcome for progressive upgrade stages. Unlike Figure 5, the figures are cumulative to reflect progressive upgrade. This illustrates the advantage of removing a small amount of mass at multiple stages along processing, with 33% energy usage providing 96% potential recovery – representing a massive and economically viable saving in processing costs.

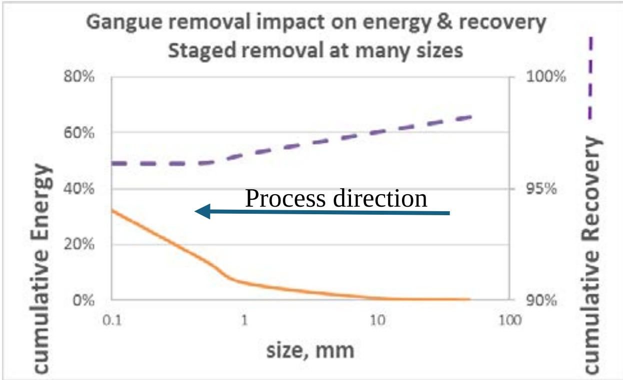

Figure 6 Cumulative recovery and energy usage for progressive upgrade

Progressive upgrading requires producing feed sizes suited to each stage of rejection or recovery, which renders the scenario in Figure 6 unachievable with conventional circuits.

4 Staged breakage

As seen in the size ranges in Figure 2 and Figure 3 for flotation and sorting, there is a strong driver to produce narrow feed size distributions to each stage of recovery or rejection. This does not favour conventional crushing-ball mill or SAG – pebble crush - ball mill (SABC) circuits. Additionally, most coarse waste rejection systems are dry processes. These factors suggest that comminution circuits should be redesigned for future process efficiencies. Stages of controlled breakage, that maximise appropriate material available in the next desired recovery/reject step, are required. This flies in the face of current approaches that embrace massive single-line processing with few stages of processing, a choice driven by capital and operating costs. To justify a change, it is necessary to fairly assess the energy and performance of lower-energy stages of breakage that are tuned to reduce the fraction of ore that requires final fine breakage.

An example of breakage data from ideal breakage product versus standard SAG milling of a porphyry ore is presented in Figure 7. Ideal breakage uses only 20% to 25% of the measured SABC circuit energy while placing most of the product in the optimal recovery zone.

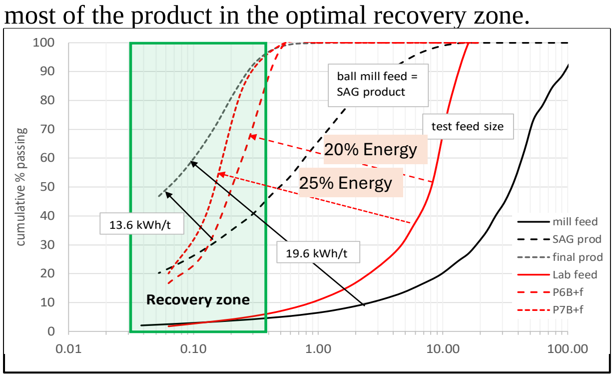

Figure 7 Ideal versus SAG milled product and energy

This provides an indication of the size of the of ideal breakage in terms of energy, with the recovery not quantified but expected to improve based on the ideal distribution of the feed for the flotation process.

5 Implications for energy and recovery

Modelling of energy use with such dramatically different outcomes, as shown in Figure 7, requires a valid approach outside methods employed in standard process design. The size specific energy (SSE) metric [4] is based on the energy to produce a fine size fraction, usually the final product size. A laboratory test has been developed to measure ideal minimum practical energy [1] quantified by SSE. This was applied to measured process data to quantify equipment efficiencies and thus allow laboratory characterisation data to be applied to real values for industrial equipment [2]. A more realistic energy use can then be applied to each chosen stage of breakage.

Figure 8 illustrates the impact on energy consumption of a hypothetical progressive upgrade scenario.

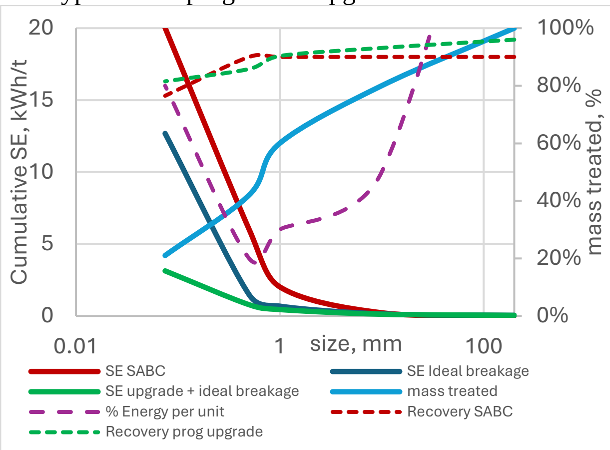

Figure 8 Progressive upgrade and energy-efficient equipment

The SABC energy trend represents business as usual with a total SE of 20 kWh/t. The energy per unit is the reduction in energy use for each stage of comminution. Doubling the energy used in blasting provides a better top-size control to the crushing stages. Applying realistic energies for ideal breakage methods across three stages enables substantial energy reduction in the size range of 10 to 0.5 mm. Below that down to 75 µm, a stirred mill is used with 20% energy reduction compared to ball milling.

When staged upgrade is then added to the process, the total energy consumption plummets. The progressive mass treated shows how much is being cumulatively removed per stage, landing on only 20% being subjected to fine grinding. The impact provides a paradigm shift of dropping from 20 to 3.1 kWh/t. This corresponds in a matching reduction in the required processing capacity as the feed mass reduces.

Recovery simulations are based on typical site recovery figures for the SABC circuit. For the progressive upgrade circuit, recoveries are based on the calculated recovery potentials of Figure 4. There are recovery losses at every upgrade stage. This has been minimised by maximising the feed size into the optimum liberation and recovery zone for each stage of recovery. The emphasis is on gangue rejection, so a lower recovery grade can be prioritised to maximise recovery at each stage. This is important to minimise the progressive losses of staged upgrade. The final recovery should be higher than for conventional mining and flotation. The envisaged stages of recovery for this scenario can be:

1. RoM: closer spacing, variable distribution of explosives, timing for controlled heave to minimise dilution - reducing losses and increasing processing grade at the mining face.
2. 10 – 30 mm: ore sorting
3. 1– 2 mm: physical separation such as gravity, electromagnetic, or electrostatic.
4. 0.4 – 0.7 mm: coarse particle flotation.
5. -0.1mm: standard flotation on regrind product

Opportunities exist for recovery of the rejected coarse particles in the 1-30 mm range by directing them to a heap leach. This allows scavenging of low grade and of mis-directed higher-grade particles. Recovery will be high in a well-constructed pad built from this controlled feed size.

The benefits include a massive reduction in energy consumption; slashing the size or removing the need for tailings dams; increased water recovery reducing fresh water needs to potentially a quarter of current.

The opportunities outlined here can have a significant impact on the design and economic assessment of future circuits. To make this a reality, the mining industry will need to advance their mindset on conducting breakage for mineral recovery, underpinned by meaningful measures of energy and efficiency.

6 References

[1] Ali, S., Powell, M.S., Yahyaei, M., Weatherley, D.K and Ballantyne, G.R., 2022. A standardised method for the precise quantification of practical minimum comminution energy. Proc XXXI IMPC, Melbourne, 22-24 Aug. Publ. AusIMM. ISBN 978-1-922295-08-5.

[2] Ali, S., Powell, M.S., Yahyaei, M., Ballantyne, G.R. and Weatherley, D.K., 2023. Assessing comminution circuit performance using precision measurement of size specific energy. Proc. Int. AG/SAG and HPGR grinding roll technology, Sep. 25-28, Pub. CIM.

[3] Ballantyne, G.R. 2016, private communication, 29 September, JKMRC, university of Queensland.

[4] Ballantyne, G.R., Peukert, W. and Powell, M.S., 2015. Size Specific Energy (SSE) – Energy Required to Generate Minus 75 Micron Material. International J. Mineral Processing vol. 139, pp. 2-6.

[5] Bond, F. C., 1961. Crushing and Grinding Calculations: Part l and Part II. British Chemical Engineering, 6, 8, 378-385, 543-548.

[6] Frausto, J.J., Ballantyne, G.R., Runge, K., Powell, M.S., Wightman, E.M., Evans, C.L., Gonzalez, P. and Gomez, S., 2021. The effect of screen versus cyclone classification on the mineral liberation properties of a polymetallic ore. Minerals Engineering, vol. 169.

[7] Hilden, MM, Powell, MS, 2017. A geometrical texture model for multi-mineral liberation prediction. Minerals Engineering, Vol 111, pp 25–35.

[8] Morrell, S., 2009. Predicting the overall specific energy requirement of crushing, high pressure grinding roll and tumbling mill circuits, Min. Eng. 22, 544-549.

[9] Powell, M.S., Hilden, M.M., Ballantyne, G., Liu, L. and Tavares, L.M. 2014. The appropriate, and inappropriate, application of the JKMRC t10 relationship. Proceedings XXVII IMPC, Santiago, Oct. Paper 767.