PEBBLES: WHAT ARE WE REALLY SENDING BACK TO OUR MILLS?

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Abstract

Coarse particles, known as 'pebbles' or 'scats', discharge from any autogenous grinding (AG) or semi-autogenous grinding (SAG) mill and often end up recirculating back to the mill feed. Sometimes, these pebbles are crushed while other times they are returned intact and considered a natural consequence of primary grinding, due to the critical energy requirement for certain sized particles.

Increasingly, the impact of pebble recycle is being scrutinized by operations dealing with competent feed. This includes the negative effect on circuit efficiency, mill capacity and even pebble crushing capacity. Operations are moving to finer feed conditions more akin to primary ball milling circuits, so why are we not assessing the impact of pebble recirculation? Have the pebbles not already proven themselves to be competent and resilient, and in fact, worthy of a higher cut-off grade compared to the remainder of the 'ore'?

The authors recently evaluated AG and SAG mill pebble samples from North American copper operations for their hardness, grade distribution and suitability for detection using x-ray transmissive (XRT) sensors. Following a laboratory protocol developed by the authors, the pebble samples showed a remarkable range of metal grades, which could be detected using the XRT sensor.

As pebble streams are prime candidates for particle sorting - due to their limited range of size and presentation on a recycle conveyor - these results support rejection of the low-grade portion of pebbles. This paper summarises these test results and estimates the increase in both mill capacity and metal grades that is possible with up to 50% pebble rejection of below cut-off grade material.

KEYWORDS

Autogenous grinding, pebbles, XRT, sorting

BACKGROUND

Primary grinding mill pebbles (or scats) are an inevitable result of screening discharge streams. Increasingly, autogenous grinding (AG) or semi-autogenous grinding (SAG) mills with competent feed are generating high pebble flowrates which are recycled back to the mill after being crushed below a nominal 'critical size'. Pebble rates (as a proportion of fresh feed) can be 30% or even higher for some AG mills with large pebble ports in their grate designs.

Over the past two decades, a number of operations have questioned the value of their mill pebbles; mainly bypassing them entirely and dumping them to ground as waste. These operations include Palabora's AG mills (Condori, 2011), Fort Knox's SAG mill (Magnuson, 2001), Kensington's ball mill (Coeur Mining, 2021) and recently Forrestania's ball mill (McCredden, 2024). It is not common to hear about a *portion* of pebbles being rejected; for example, the coarser or finer size fractions.

Kensington commissioned an x-ray transmissive (XRT) sensor sorter in 2015 to select higher-grade pebbles to return to the ball mill (Coeur Mining, 2021). These selected pebbles are 24% higher in grade than fresh feed at only 8% mass pull. Rejected pebbles are shipped offsite for use at another Coeur site.

It is suggested in this paper that crushed pebbles continue to impact mill performance. If so, should they not be well characterised to understand if all (or a particular fraction) should be rejected to improve the overall circuit efficiency? It is common to occasionally sample pebbles for overall grade compared with the fresh feed. A deeper investigation may include assay-by-size data. But what is known about the grade distribution on a particle-by-particle basis?

To better understand the composition of pebbles, samples were evaluated from North American copper porphyry operations: two SAG mill circuits and one AG mill circuit. Characterisation included grade-by-size analysis, hardness-by-size fraction and XRT sensor assessment. The dual-energy XRT sensor work was conducted by Base Metallurgical Labs in Kamloops BC using the Comex LSX-400 batch scanner.

EFFECT OF PEBBLES ON MILL CAPACITY

For competent feed, it can be shown that after crushing, pebbles continue to impact mill performance by taking up a portion of the mill volume with harder, low breakage rate material. Some years ago, an investigation into a West Australian SABC circuit treating competent feed included dumping their SAG mill pebbles for a two-hour period. The process data trends before/ after this trial are summarised in Figures 1 and 2.

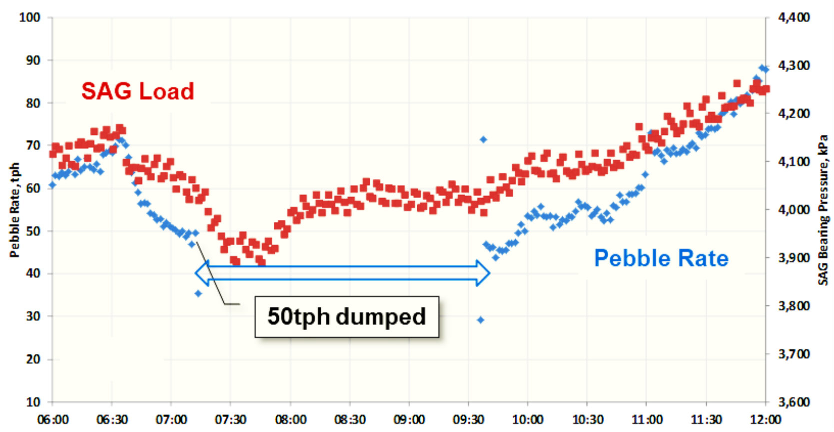

Figure 1 – SAG mill load showing period when pebbles dumped

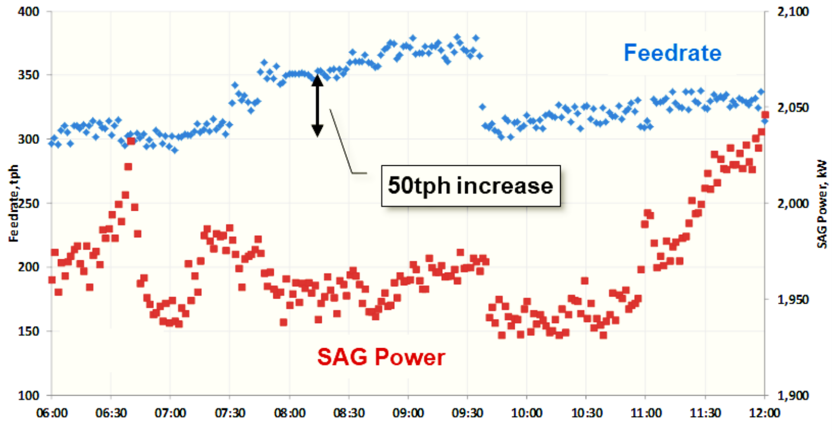

Figure 2 – SAG mill feedrate and power during pebble dumping

Normally, the 300tph feedrate generated 50tph of competent, rounded pebbles corresponding to a 17% pebble rate. Over the period when pebbles were bypassed, the mill load stabilised at a lower level as the feedrate climbed to 350tph. In other words, the fresh feedrate increase by the same amount as the pebbles being discharged. This is perhaps an extreme case as most operations would suggest *crushed* pebbles account for 40% to 70% of fresh feed, depending on ore hardness. However, if the pebble rate is 20% and a 50% pebble influence factor is used – this suggests 10% higher throughput could be achieved when bypassing pebbles.

A recent trial at a Canadian copper operation, investigated their SAG mill throughput with crushed pebble recycle versus pebble bypass (i.e. rejected completely from the circuit). Around 700 data points (five minutes each for 58 hours) were compared in terms of pebble rate (Figure 3), mill feedrate (Figure 4) and SAG mill specific energy (Figure 5). The results showed a slight increase in pebble rate with bypass off, from 12.9% to 14.6% on average. The mill feedrate increased by 6%, up to 1,887tph or 40% of the pebble rate over that period.

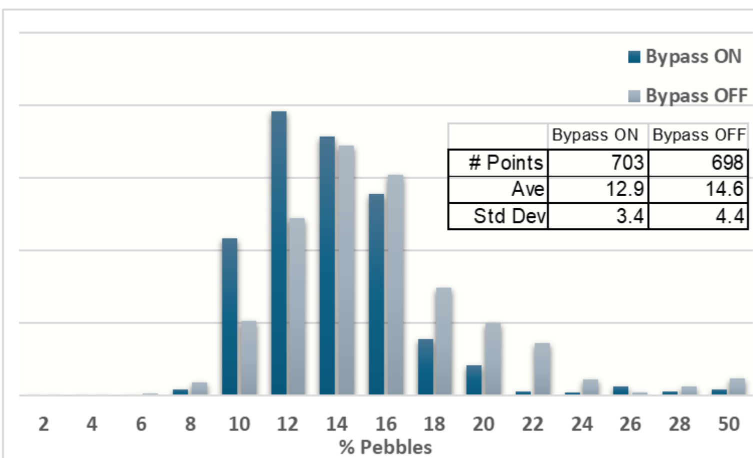

Figure 3 – SAG mill pebble rate histogram (with/ without bypass)

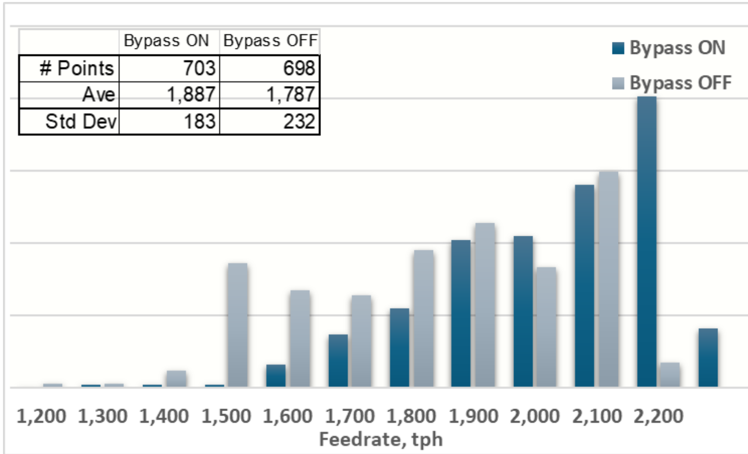

Figure 4 – SAG mill feedrate histogram (with/ without bypass)

Interestingly, the mill specific energy showed fewer deviations above 6kWh/t that were observed when the pebbles were recycled; potentially suggesting a more stable mill operation.

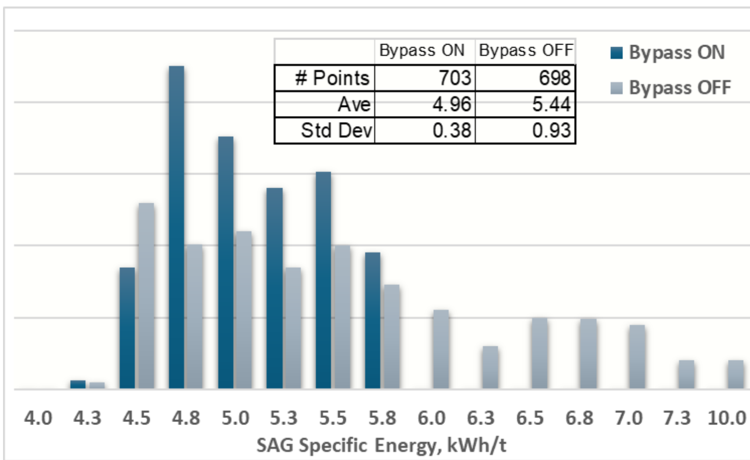

Figure 5 – SAG mill specific energy histogram (with/ without bypass)

As an example of how mill conditions can impact pebble rate, a recent paper from operation presented the Taseko Gibraltar SAG mill performance following a pulp lifter design change (see Figure 6). Pedersen et. al. (2023) reported a 4% increase in throughput, with an associated 11% reduction in mill filling and 6% to 8%increase in pebble rate.

It is proposed that pebble rate can be manipulated by adjusting the degree of impact breakage – quickly using mill speed and rock filling and more slowly with ball to rock ratio in the mill charge. Consequently, the magnitude of any gains by rejecting some/ all mill pebbles can be also manipulated to improve the overall circuit efficiency.

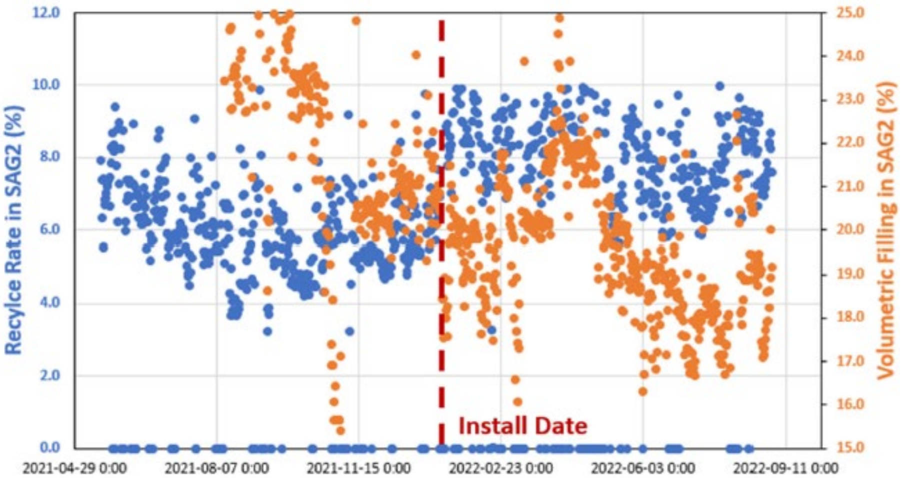

Figure 6 – SAG mill filling and recycle pre/ post pulp lifter change (Pedersen, 2023)

Although the evidence is somewhat sporadic, it is suggested that primary mill circuits with high pebble rates are sustaining these rates due to the residual effect of crushed pebbles on their discharge capacity. For competent feed material, the effect of crushed pebbles on feedrate may be 40% to 70% of the pebble rate.

PEBBLE CHARACTERISATION

To investigate the characteristics of pebbles being generated from AG/ SAG mills, bulk samples were collected from North American copper porphyry operations: three SAG mill and two AG mill samples. Characterisation included size distributions, hardness and grade-by-size analysis. Following this, particle-by-particle ranking was done on coarse and fine pebble fractions using the XRT sensor – a distribution of expected grades based on atomic density ranking was generated and checked by assaying groups of particles from each sample. (These results are discussed in *Sensor Testing* later in this paper.)

Size Distribution

Figure 7 shows cumulative size distributions for the five pebble samples studied. Differences between the mill grate openings are clearly evident with AG pebbles up to 150mm in size.

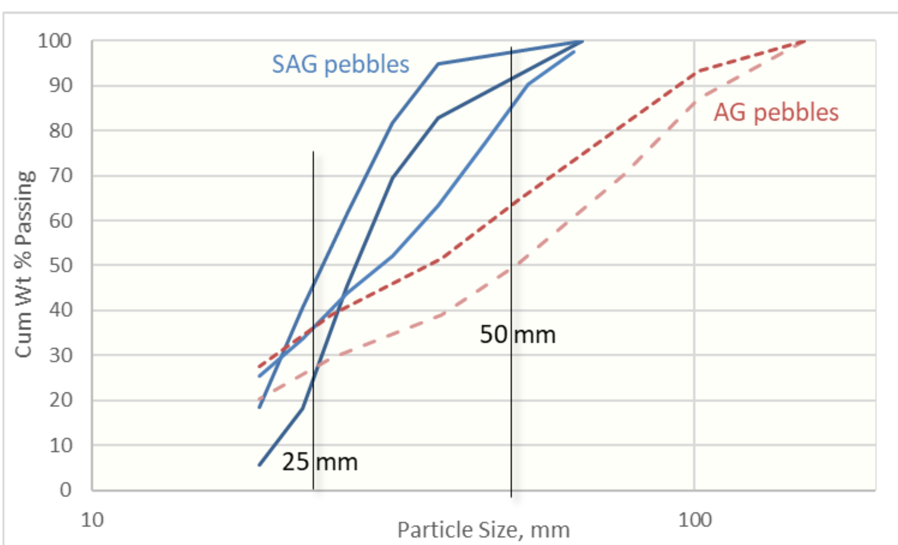

Figure 7 – AG/ SAG mill pebble size distributions included in study

In general, all samples had negligible -12mm material (typical discharge screen opening), similar mass distribution in the 12mm x 25mm fraction (20% to 50%) but were quite different above 50mm. It should be noted the AG mill sampled was fitted with 150mm grate openings and generating a pebble rate of up to 100%. Due to the difference in size distributions, the coarse and fine fractions submitted for XRT sensor testing varied between samples.

In comparison, Li presented a summary of pebble analysis for Pulang Copper at SAG 2023 (Li, 2023) which was slightly finer and mainly in the 13mm x 37.5mm size range.

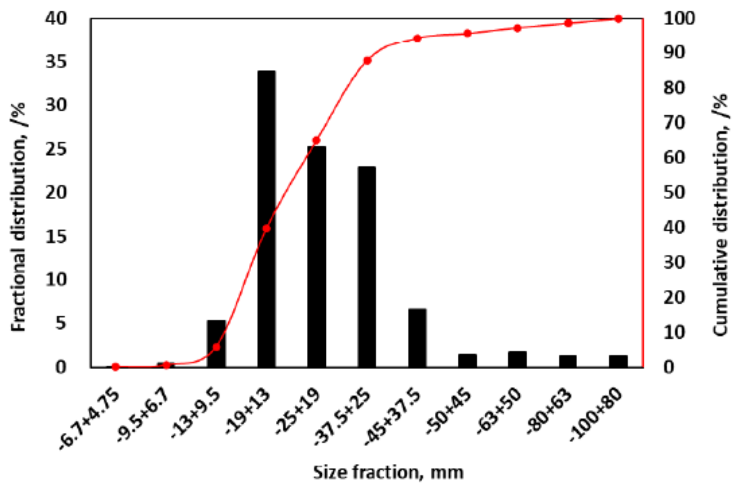

Figure 8 – Pulang Copper Pebble Size Distribution (Li, 2023)

Hardness

Pebble hardness is expected to be higher than mill feed material, but limited published information was found characterising pebble competency by size fraction. For example, if coarse pebbles are less resistant than fine pebbles to impact breakage.

In 2023, a Peruvian copper operation trialed their two parallel grinding circuits with/ without pebble bypass over a ten-day period. During the trial, pebble samples were collected for sizing, grade-by-size and overall hardness. They reported the pebbles to have a SAG Grindability Index (SGI) of 120min compared with feed SGI estimates of 88min. (These SGI values were converted to Drop Weight test parameters, with pebbles reporting an A*b of 36 and feed an A*b of 44.)

For the five pebble samples evaluated in this study, 19mm x 22mm particles were HIT tested to estimate A*b values. (For coarser sizes, samples were crushed to achieve the same test size fraction.) For the three SAG and two AG pebble samples, little trend in A*b value was noted between size fractions. Across the 19mm to 53mm fractions HIT tested for the SAG samples, all measured within 15% of the average hardness. Similarly, across the 19mm to 75mm fractions HIT tested for the AG samples, little trend with size was noted.

The copper operations did not provide original feed A*b values, so a comparison between pebble and feed hardness could not be made. Based on the samples evaluated to date, there appears to be little difference in competency between fine and coarse pebbles generated by a mill. This is based on impact breakage resistance only (i.e. A*b) and estimated on 19mm x 22mm particles using the HIT device.

Grade Distribution

Robben (2020) presented some sorting results on pebble samples collected from two Russian gold operations. In the paper, Robben provides grades for two or three fractions, with no consistent trend in grade from the +40mm down to the +8mm fractions that were sensor tested.

The Peruvian copper operation monitored overall pebble grades versus fresh feed for the two lines over the 10-day trial period. Overall, pebble grades were around 60% of the 0.29% Cu average feed grade. The variation in copper distribution for three fractions and the two parallel lines is shown in Figure 9. Both mills appear to be generating similar copper distributions in their respective pebbles; however, pebble composition does vary across the trial period particularly in the -19mm fraction.

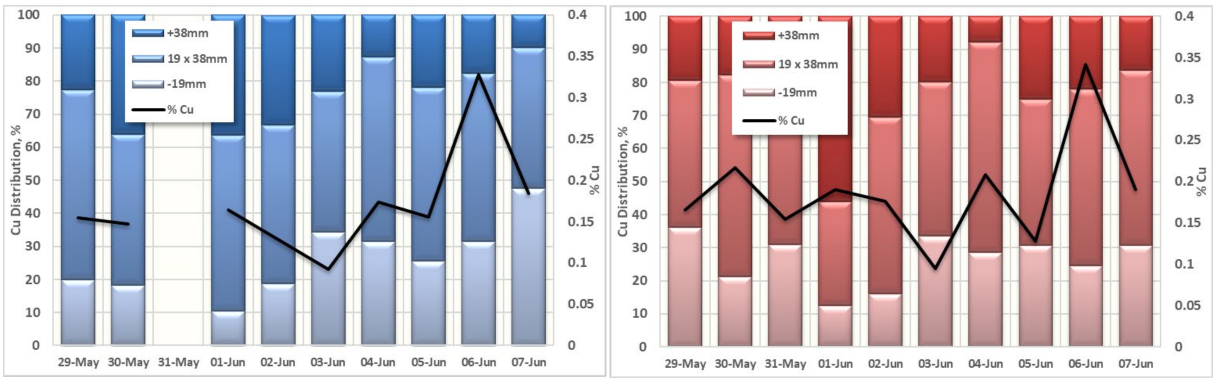

Figure 9 – Pebble Sample Copper Distribution by Size (Grinding Line 1 vs 2)

For the five AG/ SAG pebble samples evaluated, the size distributions and copper grades are all shown in Figure 10 (blue colour for SAG samples and red colour for AG). A consistent trend in grade across the different size fractions tested was not observed. This was true for both copper and sulphur grades.

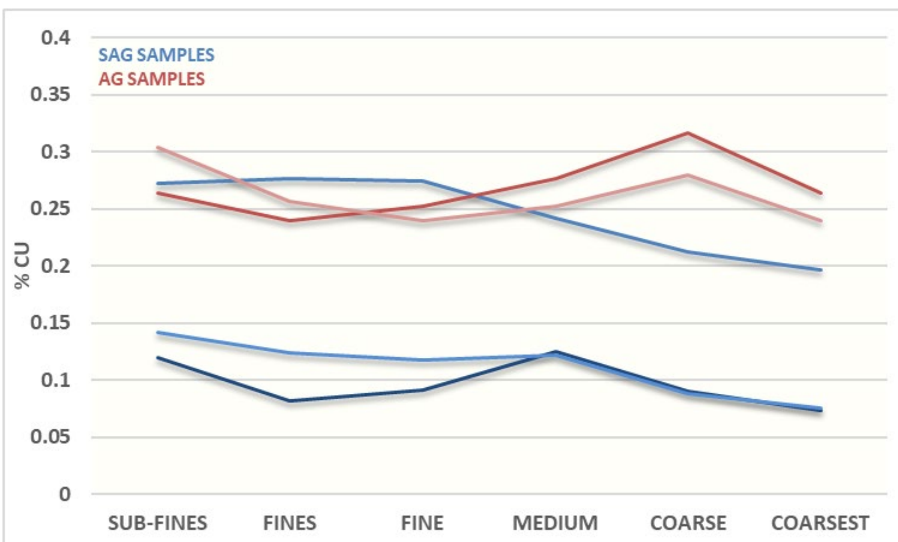

Figure 10 – AG/ SAG mill pebble grade by size distributions

A result of these relatively consistent grades across size fractions is there is little potential to preferentially recover copper by screening the pebbles. As an example, Figure 11 shows the copper recovery versus mass curve for increasing particle size for one of the SAG pebble samples. For the samples evaluated to date, screening pebbles does not seem to offer much upgrading or waste rejection.

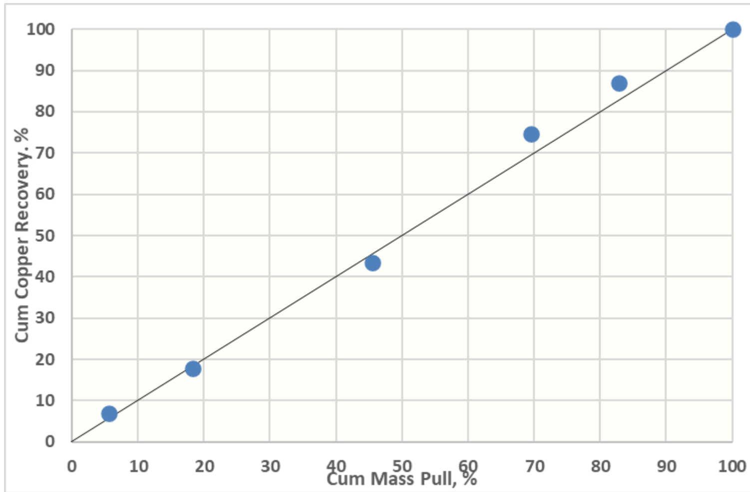

Figure 11 – Example mill pebble size deportment recovery vs mass pull

Based on the sample data reviewed, pebble characteristics showed:

- Hardness was higher than mill feed in impact breakage resistance
- Size distribution varied greatly, depending on mill conditions
- For copper porphyry samples, hardness was consistent across size
- Grade was generally lower than fresh feed
- Grade distributions showed limited potential to upgrade by screening.

Therefore, the economic benefit from pebble bypass would be entirely due to the removal of a hard component from the feed (despite being crushed to below critical size), and the grade differential from supplementing pebbles with higher-grade fresh feed.

What was not investigated in the gross properties listed above was whether metal grades were consistent on a *particle-by-particle* basis, which could be identified using an XRT sensor.

SENSOR TESTING

Mill pebbles are an obvious target for particle sorting. They are screened of fines, have a limited range in size (for SAG mills in particular) are conveyed back to the mill and generally are washed (making x-ray fluorescence or XRF a possible candidate sensor).

Robben (2020) presented sorting results for two Russian gold operations which used either laser or XRT sensors to identify quartz-hosted or sulphide-associated gold. For a 0.75g/t Au pebble sample, a laser sensor achieved 84% and 73% gold recovery in the +40mm and +20mm fractions to only 41% and 33% mass pull. The main achievement is a 0.3g/t Au waste fraction of high mass. This is evidence a large proportion of the mill pebbles were quite barren of gold but were being circulated regardless.

As a second example, Robben (2020) showed results for a 1.23g/t Au pebble sample using an XRT sensor where 58% and 68% gold recovery in the +20mm and +40mm fractions was achieved to only 22% mass pull. Once again, a 0.3 to 0.6g/t Au waste fraction was the principal achievement – removing waste from a stream returning to the mill for grinding.

Li presented some interesting results from Pulang Copper (Li, 2023) using XRF as a sensor to measure the grade of pebbles sized into two fractions: 16mm x 31.5mm and 31.5mm x 63mm. For both fractions, Li measured the grade of 200 individual particles, as shown in Figure 12 and Figure 13.

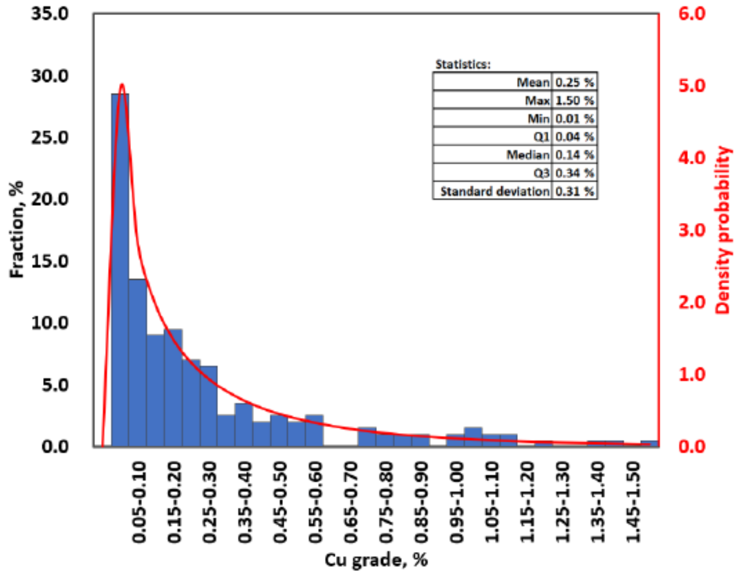

Figure 12 – Pulang Copper 16mm x 32mm Pebble Copper Distribution (Li, 2023)

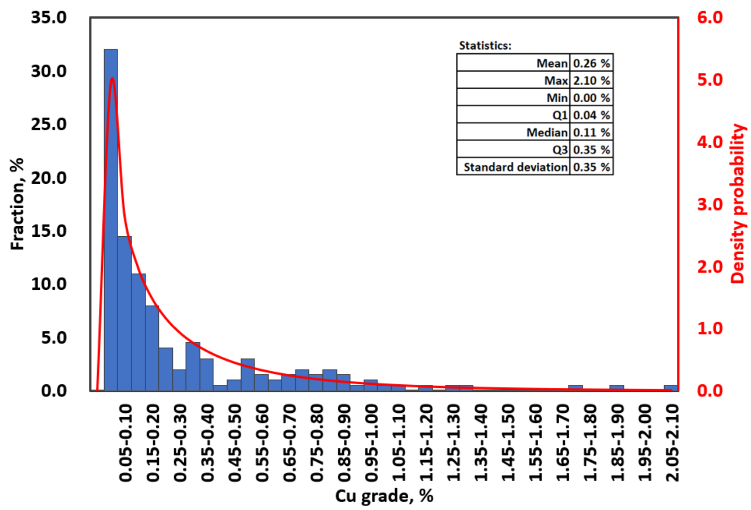

Figure 13 – Pulang Copper 32mm x 63mm Pebble Copper Distribution (Li, 2023)

Both fractions reported a mean grade of ~0.25% Cu with individual particles up to 1.5% Cu for the fine fraction and 2.1% Cu for the coarse fraction. It appears the pebble grades follow a lognormal distribution and mirrors the study detailed in this paper looking at pebbles from copper porphyry operations.

Following the initial bulk characterisation of the five pebble samples, this study looked at these samples on a particle-by-particle basis, using the XRT sensor available at Base Metallurgical Labs. For each sample, coarse and fine fraction sample sets were scanned using the dual-energy XRT sensor (see Figure 14 and Figure 15 for SAG and AG mill pebble images).

Around 600 particles were scanned in each fraction and XRT response values were ranked with six groups selected for assay. Note: not every particle was assayed as done by Li using XRF. Therefore, only six assays are reported for each coarse and fine fraction for the samples evaluated.

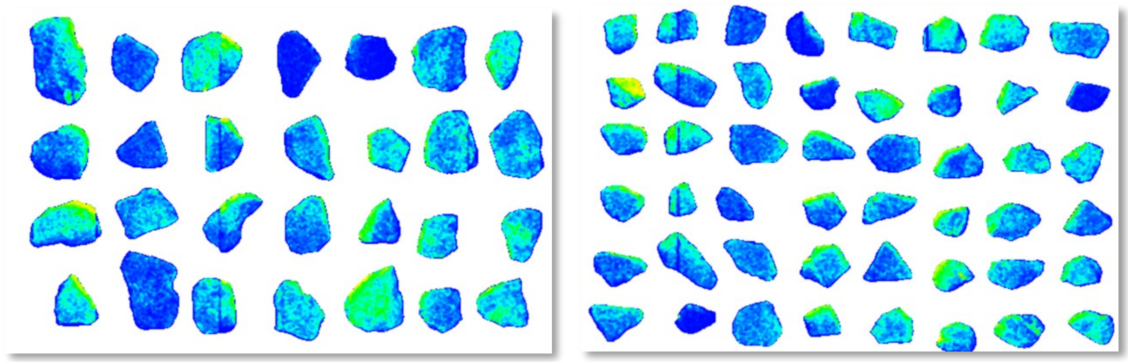

Figure 14 – SAG mill pebble XRT image scans (left: coarse, right: fine)

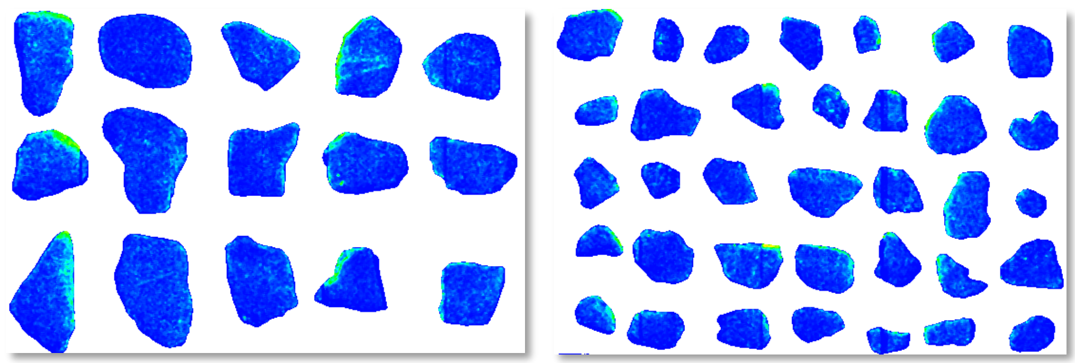

Figure 15 – AG mill pebble XRT image scans (left: coarse, right: fine)

The XRT image scans clearly showed a range of atomic densities present in the individual SAG mill sample particle sets; however, the AG mill samples appeared to be far more homogeneous in composition.

Figure 16 shows the SAG mill copper and sulphur grades by XRT response group, from low response to high response, influenced primarily by atomic density. The SAG mill samples showed particle groups assaying up to 1% Cu from a 0.10% Cu overall pebble sample. This agrees with the lognormal distributions reported by Li using an XRF sensor.

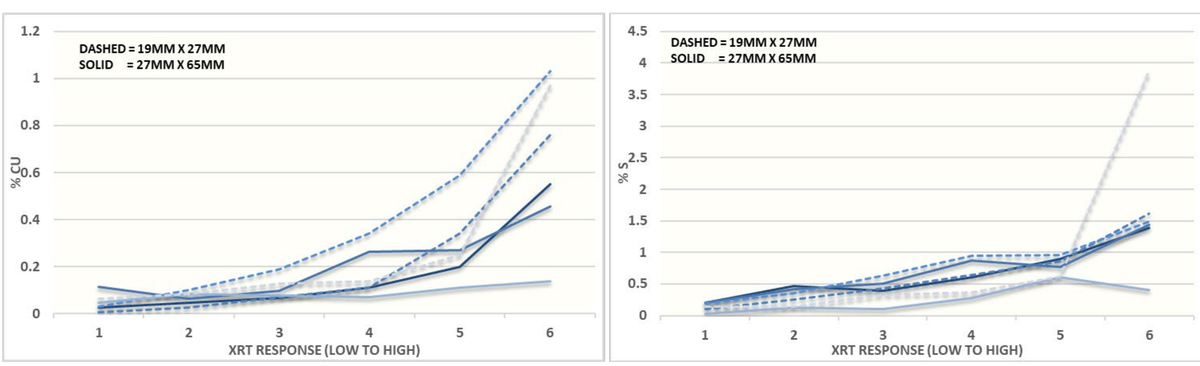

Figure 16 – SAG mill pebble XRT group grades (left: copper, right: sulphur)

The results for the two AG mill samples showed a narrow copper and sulphur grade distribution, with the highest XRT response fraction only assaying 0.45% Cu (see Figure 17). Copper and sulphur grades followed each other, but overall, the two AG mill pebble samples were much lower in sulphur grade compared with the SAG mill samples and possibly this limited the amenability of the XRT sensor to detect differences in atomic density.

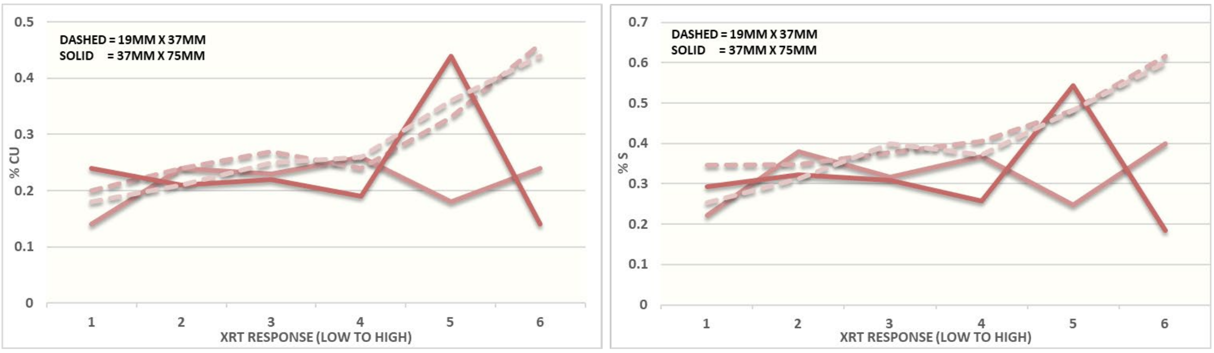

Figure 17 – AG mill pebble XRT group grades (left: copper, right: sulphur)

It is not suggested that AG mill pebble samples will not exhibit the same metal grade distributions shown in the SAG mill pebble samples studied. This is clearly orebody dependent and the AG mill operation doesn't have the same orebody characteristics (i.e. grade homogeneity) as the SAG mill pebbles included in the study.

The distribution of particles by XRT response for the two size fractions are shown in Figure 18 and Figure 19 for one of the SAG mill pebble samples.

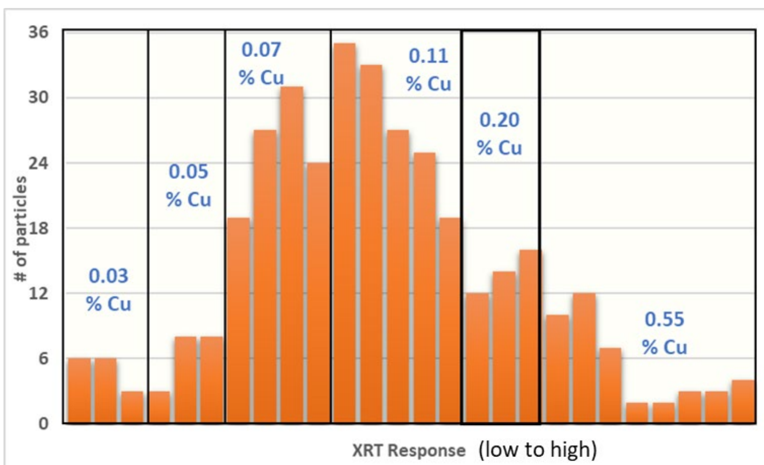

Figure 18 – SAG mill pebble 27mm x 65mm XRT response distribution

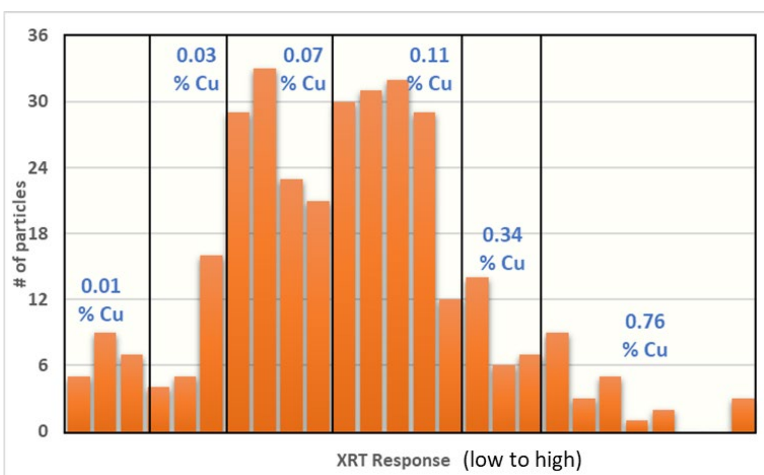

Figure 19 – SAG mill pebble 19mm x 27mm XRT response distribution

For both fractions, only the last two groups (right side) are associated with reasonable copper grades. The first four groups (left side) are well below cutoff grade for this operation. As suggested by Li (2023), the copper grades present in the pebble samples appear to follow a lognormal distribution with a long tail of high-grade copper particles.

Plotting the XRT response curve for this SAG mill sample in terms of copper recovery versus mass pull, Figure 20 shows 80% of the copper in both fine and coarse pebble fractions is present in ~50% of particles.

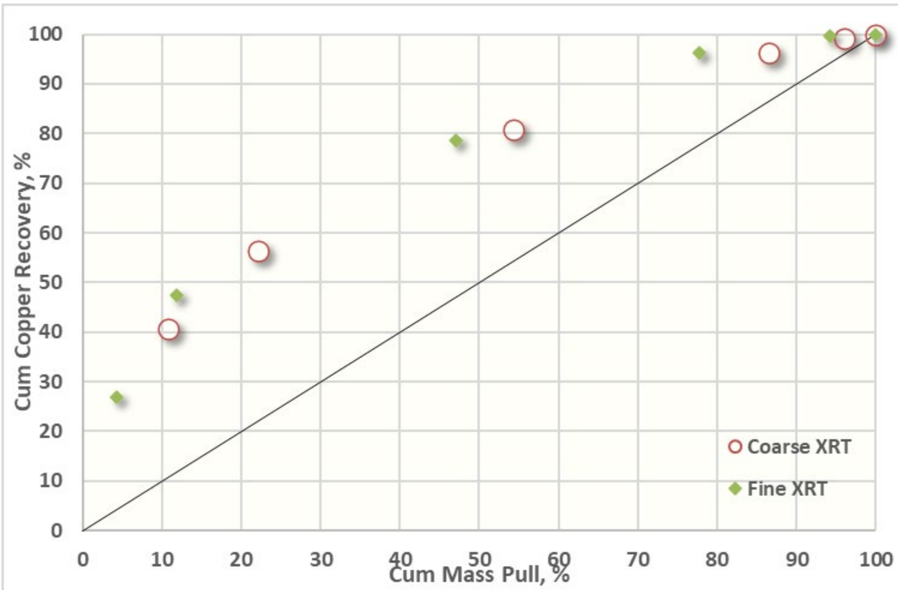

Figure 20 – SAG mill pebble XRT deportment recovery vs mass pull

These results provide further evidence of the range of metal grades present in some pebble samples; in addition, these particles can be identified using sensors (XRT in this case, XRF for Li as well as laser for Robben).

The results of the study on these five pebble samples suggest an orebody dependent characteristic of pebbles with a wide range of grades, despite the *overall grade* in each size fraction not differing from others. This particle-by-particle variability can be detected using a number of sensor types and would allow a high mass, very low-grade waste stream to be separated from the mill pebbles.

The current pebble characterisation and sensor study will continue to look at other ore types such as polymetallic/ massive sulphides and a range of gold ores, as further pebble samples become available. In addition, further copper porphyry samples will be collected under a range of mill operating conditions to investigate the premise that pebble characteristics change with mill breakage conditions.

ECONOMICS OF PEBBLE REJECTION

To illustrate the potential of pebble sorting, the results from on/ off pebble bypass trials will be used for preliminary economic evaluations.

The 10-day trial completed by the Peruvian copper operation showed pebble samples to carry 60% of the copper feed grade. Rejecting pebbles resulted in a 2.2% increase in overall copper grade as well as a 2.4% increase in throughput. This equated to $6M in additional revenue per year after accounting for the cost of hauling pebbles to a stockpile.

Similarly, the on/ off pebble bypass results for the Canadian copper operation suggested the pebble copper grade to be 70% of the feed copper grade. Bypassing pebbles resulted in a 6% increase in throughput which equated to $21M per year in additional copper sales, after discounting the cost of pebble rehandle.

These benefits are simply from bypassing pebbles, resulting in higher feed grades and higher throughput. Consequently, consideration must be given to the generation of a growing pebble stockpile, or “reserve”. Do the bypassed pebbles constitute waste, in which case this reduces total metal units from the resource, or can the value contained in pebbles be strategically processed. Consider the option of a particle sorter to reprocess the pebble stockpile so the sorting capacity is not expected to keep up with the mill pebble rate, often a key deterrent and limitation to the viability of sorting technology. The sorting operation can in essence be decoupled from the operation to conduct a stand along economic assessment.

Based on the results shown in Figure 20, 80% of the copper rejected in a pebble stockpile could be recovered to 50% of the mass. This represents a 160% increase in pebble grade. However, if the pebbles are 65% of the plant feed grade, this 160% upgrade only returns it to the original feed grade. Instead, a sensor sorting unit could be used to extract a high value component – like suggested for the Kensington operation. More importantly, reprocessing the pebble stockpile could isolate a true waste stream and not a variable mixture of pebbles in a poorly characterised stockpile. The exact high value component of the pebbles would vary project to project based on economic considerations and other sample characteristics, including hardness, metal recovery, and other downstream process considerations.

SUMMARY COMMENTS

Primary mill pebbles are a consequence of screening coarse particles from the discharge flow of grinding mills; recirculating them back to the mill is necessary, as they cannot be processed downstream. It is conventional practice to crush pebbles below ‘critical size’, but for competent feed, they still have an impact on mill throughput and performance. A number of operations have performed on/ off pebble bypass trials to quantify the impact of pebble recycle. For competent feed and mills with higher pebble rates, the economics of sorting can be justified but pebble rehandle costs may negate the benefits.

In general, it is a *housekeeping issue* as to why pebbles are returned to the mill. It is easier to grind them, send them through the plant (despite being lower in grade) and have them end up in the tailing pond rather than handle them as a separate byproduct.

A review of published results as well as an ongoing study into pebble characteristics has revealed a number of broad generalisations:

- For competent feed, 40% or more of the pebble flow is deducted from the feedrate, even for crushed pebbles.
- Pebble size fractions vary with mill conditions and feed properties, and in particular, the grate design.
- Pebble hardness appears consistent across the size fractions but is generally harder than fresh feed.
- Grade-by-size data suggests limited deportment of metal to certain fractions.
- For copper porphyry pebble samples, a wide range of copper grades occur for both coarse and fine fractions.
- The range of particle-by-particle grades can be detected by a range of sensors (e.g. XRT, XRF, laser).
- The homogeneity of pebbles will vary by project, and may determine if pebbles can be selectively processed to extract a high value component.

Supplementing pebble bypass with a stockpile reclaim process involving particle sorting can generate a concentrated mass, high value byproduct stream. More importantly, it can identify and segregate a significant amount of true waste from a variable and poorly characterised stockpile of rejected pebbles.

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