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INSIGHTS INTO DIFFERENT OPERATING PHILOSOPHIES – INFLUENCE OF A VARIABLE ORE BODY ON COMMINUTION CIRCUIT DESIGN AND OPERATION

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ABSTRACT

The Kansanshi copper ore body consists of distinct sulphide and oxide zones as well as a variable transitional zone containing both oxide and sulphide minerals which is referred to as the mixed ore zone. All three ores exist in exploitable quantities for the life of mine. The impact and abrasion resistance characteristics of the different ore types vary over a considerably wide range. To match the variation in mineralogy and mechanical competency across the ore body, different design circuits were installed for the efficient processing of each ore type. It is evident from the installed comminution equipment capabilities of the different circuits that the ore competency distribution of the Kansanshi reserve informed the original plant design making process. Current specific energy consumptions associated with the final circuit products are consistent with the differences in competencies observed amongst the ore types. A series of calibration surveys were performed in order to explore the operational envelope of the three circuits. This paper presents some insights into the operating philosophies employed in the comminution of the different ore types at the Kansanshi operation.

KEYWORDS

SAG mill, ore characterisation, volumetric filling, throughput.

INTRODUCTION

Kansanshi Mine is located 180 km to the northwest of the Copperbelt town of Chingola and some 10 km north of the town of Solwezi in Zambia. It is the largest copper mine in Africa, with production capabilities of 340,000 tons of copper and in excess of 120,000 ounces of gold per annum. The mine is 80% owned by Kansanshi Mining PLC, a First Quantum subsidiary. The mine is fairly young, having started operating in 2005. It is envisaged that copper production will exceed 400,000 tonnes in the current year as a result of an on-going expansion project aimed at increasing production capacity.

Mining activities involve operation of two open pits that produce three ore types namely sulphide, oxide and mixed ores. All three ores are crushed and milled before concentration and extraction. Oxide ore is floated (to recover the sulphide minerals within the ore), and then leached to extract the acid-soluble copper from the oxide minerals, which is thereafter recovered by solvent extraction and electrowinning to produce copper cathode. Both the sulphide and oxide minerals within the mixed ore are recovered by flotation, to yield a copper concentrate. In the case of the mixed ore, controlled potential sulphidisation is required to render the oxide minerals hydrophobic for flotation – these minerals are naturally hydrophilic, and although acid soluble, the gangue acid consumption of this ore would be too high for leaching to be a feasible option for extraction.

The differences in strength characteristics of the Kansanshi ores are a manifestation of the mineralogical variation observable along a vertical traverse of the reserve, with the oxide ore at the top and the more competent sulphide ore at the bottom of the ore body. Table 1 lists the impact and abrasion resistance parameter values of the Kansanshi ores. The values were obtained from the standard JK Drop-Weight test which provides ore specific parameters for use in the JKSimMet Mineral Processing Simulator software. In JKSimMet, these parameters are combined with equipment details and operating conditions to analyse and/or predict SAG/autogenous mill performance.

Table 1 - Impact and abrasion resistance parameter values of Kansanshi ores

Ore	Impact (A*b)		Abrasion (t_a)	
	Value	Category	Value	Category
Sulphide	51.0	medium	0.36	hard
Mixed	47.9	medium	0.54	moderately soft
Oxide	64.2	soft	0.76	soft

Sulphide ore is characterised by medium resistance to impact breakage and moderately high resistance to abrasion. The mixed ore zone also presents medium impact breakage resistance but with moderately soft resistance to abrasion. The oxide ore is characterised as soft with respect to both impact and abrasion resistance. Due to different downstream processing methods Kansanshi Mine PLC employs three parallel grinding circuits each dedicated to processing one of the three ores. The operation of multiple lines is testimony to the challenge of designing a single line robust enough to process a highly variable feed source such as the Kansanshi ore reserve.

The sulphide and mixed ore circuits employ secondary crushing before their respective SAG feed stockpiles as a result of the fairly high impact resistance associated with these ore types, while the less competent oxide ore has a single crushing stage before the SAG mill feed stockpile. All three circuit configurations are based on the classic SABC (**SA**G - **B**all mill- **C**rusher) design. Equipment specifications for the three circuits are listed in Table 2.

Table 2 - Milling circuit equipment specifications

Parameter	Sulphide Circuit		Mixed Circuit		Oxide Circuit	
	SAG Mill	Sec Mill	SAG Mill	Sec Mill	SAG Mill	Sec Mill
Diameter (m)	9.442	6.1	5.8	5.08	4.6	5.08
Length (m)	5.926	9.3	9.18	9.1	8.68	7.1
Feed trunnion dia. (m)	2.1	1.6	1.6	1.6	1.68	1.43
Feed end Cone Angle (deg)	20	15	15	15	0	-
Discharge end Cone Angle (deg)	20	15	15	15	0	-
Grate size (mm)	35	-	60	-	30	-
Pebble port size	-	-	100	-	50	-
Grate Open Area (%)	3.2	Overflow	-	Overflow	-	Overflow
Mean rel. pos. of grate aperture	0.88	Overflow	0.88	Overflow	0.88	Overflow
Speed (% critical)	75	75	75	75	Variable	75
Installed power (MW)	12	5.8	5.2	5.8	3.55	3.5

The sulphide circuit consists of primary and secondary grinding stages, both served by a common nest of eight cyclones (Figure 1). SAG mill pebbles are recycled to the primary mill after crushing. The SAG mill screen undersize joins secondary mill product in a common sump that supplies the cyclones with feed. The cyclone underflow provides the only feed to the secondary ball mill. A small percentage of the cyclone underflow is recycled to the SAG mill by means of a regulated pinch valve, a design that is meant to provide additional means of controlling in-mill rheology. The cyclone underflow also provides raw feed for heavy mineral pre-concentration through gravity means using the Falcon continuous concentrator technology.

The mixed circuit consists of primary and secondary grinding stages each served by a dedicated product sump and a separate nest of seven cyclones each. A schematic of the mixed flow diagram is shown in Figure 2. Cyclone underflow streams from both nests constitute feed to secondary milling. Two Falcon concentrators installed in the circuit derive feed from part of each of the two cyclone underflow streams after screening off plus 2 mm size material.

The mixed circuit design includes the flexibility of feeding fresh feed to the ball mill at a predetermined rate relative to the primary mill depending on the quality of the fresh ore. Both mill products are screened for pebbles on discharge through trommel screens. A pebble crusher services the combined pebble stream and the crushed pebbles are recycled to the secondary mill.

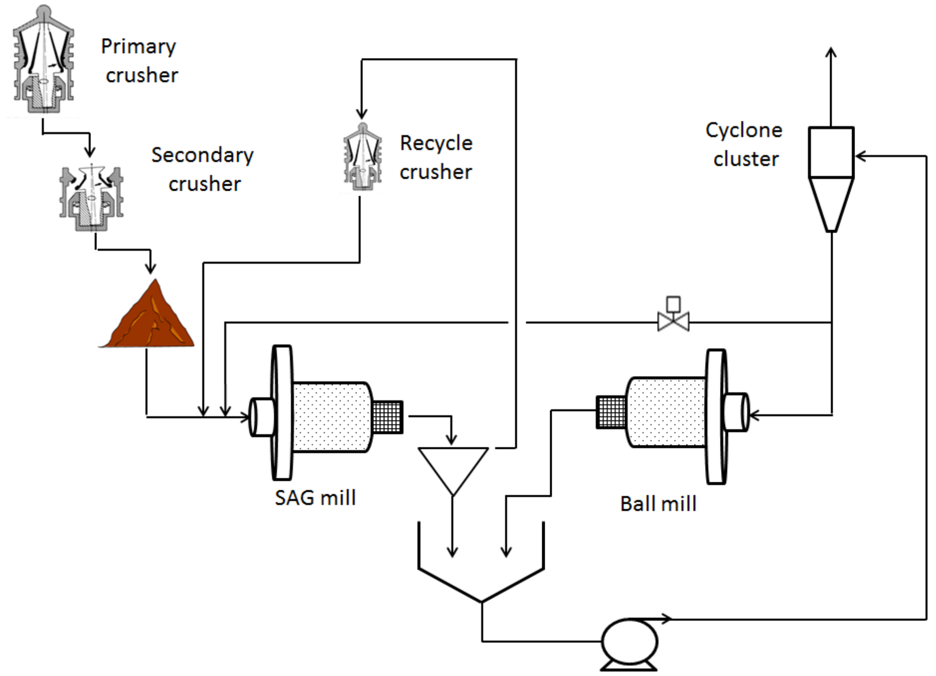

Figure 1 - Sulphide Circuit flow diagram

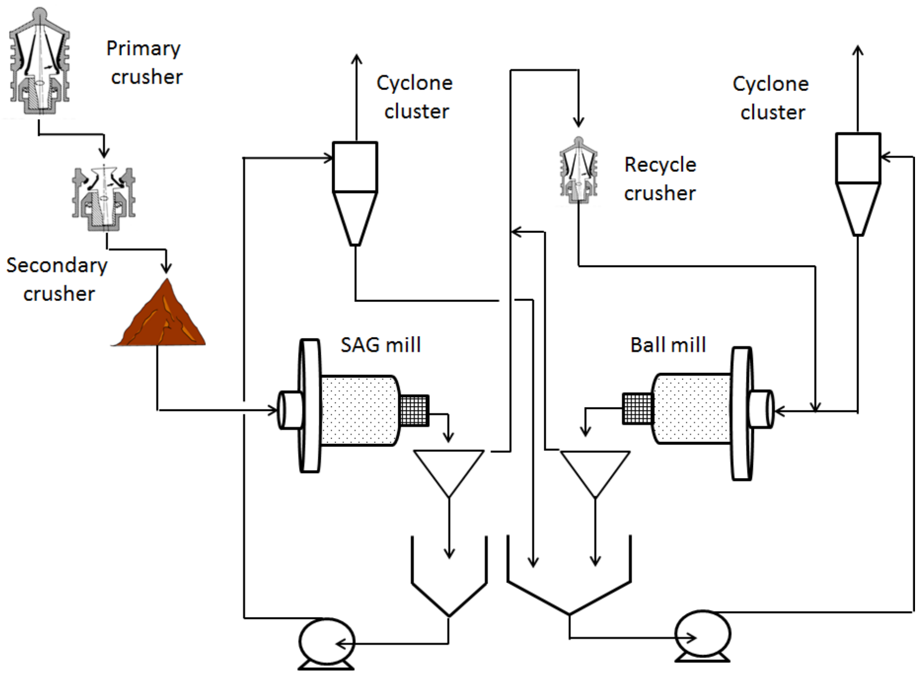

Figure 2 - Mixed Circuit flow diagram

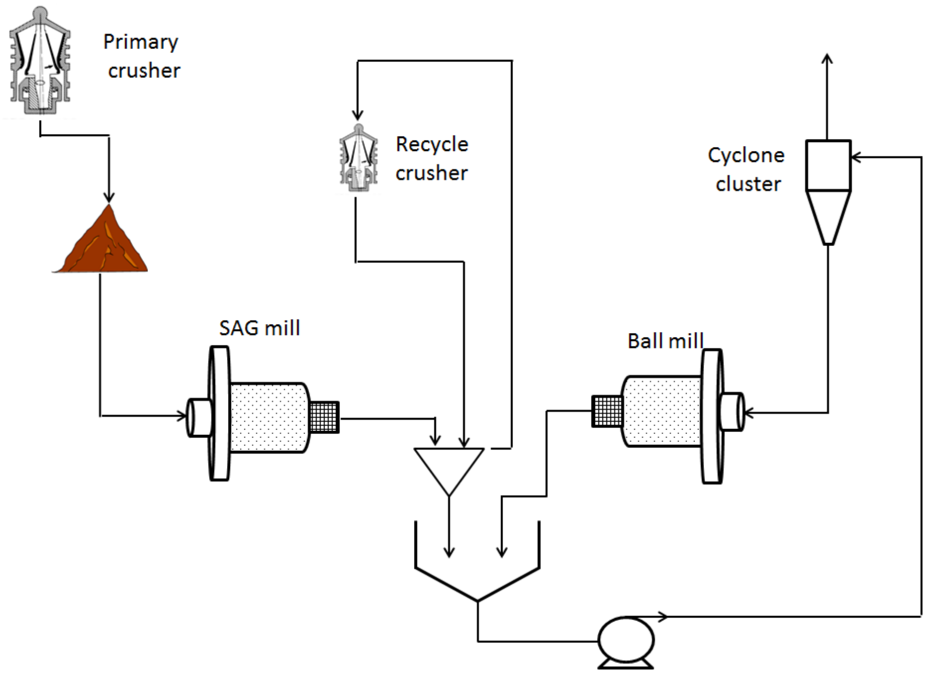

Figure 3 - Oxide Circuit flow diagram

The oxide circuit consists of primary and secondary grinding stages, both feeding a nest of 7 cyclones. Figure 3 shows a schematic of the oxide flow diagram. Here, the Falcon concentrators are supplied with screened mill product compared to the sulphide and mixed circuit configurations where feed to the respective heavy mineral concentration circuits is sourced from the cyclone underflow. SAG mill pebbles are re-directed to the SAG screen after crushing, a significant design variation from the sulphide and mixed circuit configurations. This is in addition to the absence of secondary crushing before the SAG feed stockpile.

This paper presents some insights into the operating philosophies employed in the comminution of the different ore types at Kansanshi Mine. The insights are also supported by data from the calibration surveys performed on all three comminution circuits.

CIRCUIT PERFOMANCE

Two full surveys were conducted per circuit at conditions as close to steady state as possible. All key streams were sampled and corresponding operational information such as feed rate, mill load, mill power, cyclone pressure, and flow rates of water and slurry were recorded in accordance with survey methodology guidelines suggested in Napier-Munn *et al.* (2005).

Grinding Circuit Models

Models of the major equipment were constructed in JKSimMet using dimensions and process data (stream solids flow rates, percent solids and size distributions) collected from trends and samples taken during the surveys. Mass flow rate and particle size analysis data were first reconciled using the mass balance simulator in JKSimMet prior to model fitting. The equipment models fitted include the SAG mill and ball mill models; vibratory screen, recycle crusher and cyclone models in JKSimMet.

The testwork was designed to explore the throughput capabilities of the current circuit configurations. In closed SAG/ball mill circuits, conditions in the SAG mill mainly determine circuit throughput while ball mill and cyclone operations largely control product grind (Mainza *et al*., 2011, 2015; Putland, 2005). As a result, the throughput performance evaluations in this study were centred primarily on assessing the SAG mill response to maximum throughput conditions. The SAG model in JKSimMet Software provided a useful investigative tool for analysing breakage rates in the SAG mill in order to understand the throughput capabilities of the three circuits.

The SAG model in JKSimMet is based on a plot of breakage rates fitted at five knots located at different particle sizes. This relationship is expressed as a continuous function on logarithmic co-ordinates using a cubic spline function at the knots positioned at the particle size values of 0.25, 4.0, 16.0, 44.8 and 128mm. Hence the model parameters are the $\log_e$ (breakage rate) values at these five knots. The appearance function is determined for each size fraction, based on the impact breakage and abrasion parameters (A, b, and t_a). The A, b, and t_a are obtained from Drop Weight test results or SMC Test® results. A simple classification function is used to model discharge from the mill.

Survey Results

Performance results from the surveys conducted on the three comminution circuits at Kansanshi are shown in Table 3. Two sets of results are listed for each circuit representing the two surveys conducted under different throughput conditions.

Table 3 – Circuit Performance data for the Sulphide, Mixed and Oxide Circuits

Variable	Units	Sulphide circuit		Mixed circuit		Oxide circuit	
		Survey 1	Survey 2	Survey 1	Survey 2	Survey 1	Survey 2
Throughput	tph	1333	1596	946	1075	977	962
SAG Feed, F80	mm	70.45	70.45	72.35	71.85	143.8	99.5
SAG Feed, <1.0 mm	%	8.6	8.6	20.0	13.5	29.7	35.6
SAG Prod., <1.0 mm	%	64.9	65.8	49.7	77.0	73.3	52.5
SAG Prod., <212 µm	%	39.1	37.7	32.7	40.0	44.7	35.8
SAG Power cons.	kW	11206	10875	4514	5017	2207	2487
SAG Mill speed.	% crit.	75	75	75	75	75	79
SAG Spec. En. Cons.	kWh/t	8.4	6.8	4.8	4.7	2.3	2.6
SAG Vol. Filling	%	33.7	26.6	21.9	37.2	32.8	30.5
SAG Ball Filling	%	20.3	20.3	18.2	18.2	18.5	18.5
Circ. Load to SAG	%	346	301	-	-	-	-
Secondary Mill Power	kW	5451	5232	4177	4137	2572	2632
Circuit Spec. En.	kWh/t	12.5	10.0	9.2	8.5	4.9	5.3
Circuit Prod. P80	mm	0.118	0.167	0.239	0.272	0.210	0.232
Circuit Prod. <75 µm	%	69.4	60.0	45.4	43.2	52.3	47.6

Sulphide circuit

For the sulphide circuit surveys, a high throughput of 1596 tph was observed at a 26.6% volumetric filling of the SAG mill while the circuit achieved a lower 1333 tph at a higher volumetric filling of 33.7%. Volumetric filling is the most notable distinguishing characteristic between the two surveys. Notably, the throughput obtained at 26.6% volumetric filling is in agreement with flow rates obtained at around 25% volumetric filling that the authors have observed from other plants employing SAG mills and ores with similar strength characteristics.

At constant mill speeds, volumetric filling is a significant factor in determining the extent and mode of breakage in AG/SAG mills. The predominant mode of breakage in turn influences throughput, product quality and consequently the energy efficiency of the circuit. Figure 4 shows the SAG mill breakage rate distributions extracted from the JKSimMet for the two sulphide circuit surveys.

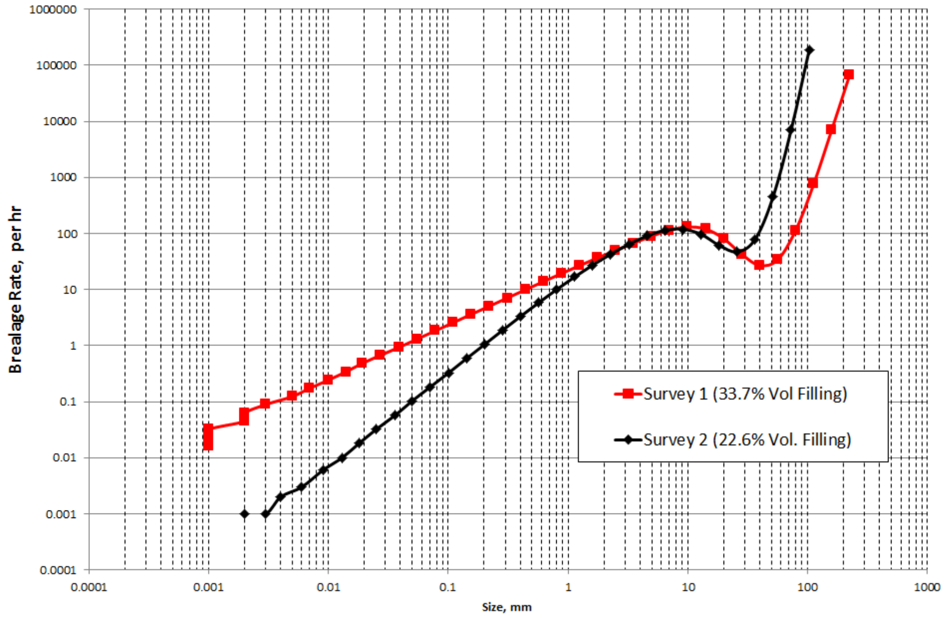

Figure 4 - Breakage rates for the Sulphide SAG mill from the survey data

It is evident from Figure 4 that breakage rates were higher at the coarse end for the test performed at 26.7% filling compared to that conducted at 33.6% filling. The elevated coarse ore breakage rates for the 26.7% filling test may partly explain the higher throughput observed for this test. Low filling degrees are normally associated with aggressive impacts in the mill, a condition that promotes high throughput.

However for this ore type, the test performed at the higher filling degree exhibited a lower throughput, although the test produced a significantly higher percentage of sub 75µm in the circuit product compared to the 26.7% volumetric filling degree test (Table 3). It is clear from Figure 4 that the breakage rates for the 33.6% filling degree test were significantly higher at the fine end of the particle size distribution compared to the 22.7% filling test results, a condition responsible for the high generation of fine material observed in the final product.

From observations made in Survey 2 it can be surmised that a reduction in volumetric filling promotes high energy (impact) breakage in AG/SAG mills leading to an increase in throughput and a reduction in product grind as observed for the lower filling test. This is usually observed at high mill speeds where the extra kinetic energy imparted to the charge enhances impact breakage of coarse rock (Napier-Munn *et al.*, 2005). In the case of mill filling, the extra energy responsible for the increased coarse particle breakage is derived from the additional height provided by the reduction in volumetric filling.

Conversely, higher volumetric filling rates are known to promote low energy (abrasion) breakage as a result of the increase in surface area made available for fine grinding. An increase in product fineness generally ensues, a phenomenon readily observable in more sensitive configurations such as single stage AG/SAG operations (Putland, 2005). The increased SAG mill and circuit product fineness for the 33.6% filling degree test suggests that abrasion breakage is dominant in the sulphide SAG mill under these conditions. However, the elevated specific energy consumption and increasing circulating load indicate deteriorating efficiency at the high volumetric filling regime at which the SAG mill was operated in this test.

Oxide circuit

The oxide SAG mill is equipped with variable speed control. In AG/SAG operations, variable speed is a useful tool for regulating throughput and specific energy consumption. Increasing mill speed usually enhances impact breakage conditions in the mill, leading to higher throughputs.

The surveys for the oxide circuit were aimed at assessing the effect of speed on throughput and product grind. The oxide SAG mill is normally operated between 75% and 79% of critical speed at Kansanshi (Table 3). To avoid impacting on production the surveys were structured with one test at 75% and the other at 79% of critical.

No increases in throughput were observed when the mill speed was changed from 75% to 79% of critical speed during the testwork. Contrary to expectations a marginal decrease in throughput occurred at the 79% critical speed even though the volumetric filling for this test was lower. The power drawn by the SAG mill increased from 2207 kW to 2487 kW as a result of the increase in speed from 75% to 79% of critical, leading to an increase in the specific energy consumption for the entire circuit from 4.9 kWh/t to 5.3 kWh/t.

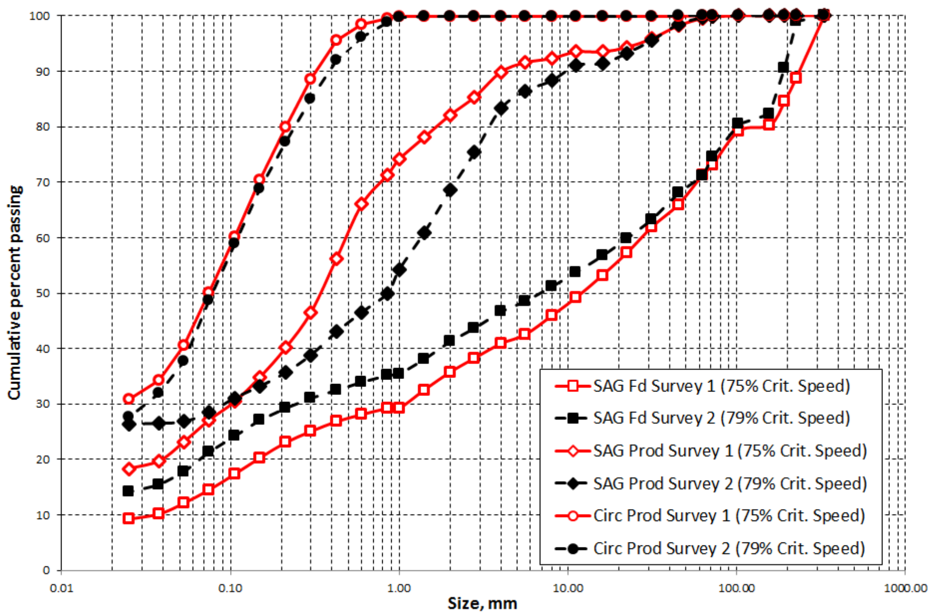

Figure 5 - Comparison of particle size distributions of the oxide circuit surveys

Figure 5 compares the particle size distributions of the SAG feed, SAG product and circuit product for the surveys performed at the two different speeds on the oxide circuit. Despite operating with a coarse feed the test performed at 75% critical speed produced the same product quality as the one performed at 79% critical speed. The results showed that a 43% net production of sub 1mm from SAG mill was achieved in the 75% critical speed test compared to 17% net production of fine material during the 79% of critical speed test (Table 3).

As shown in Figure 6, breakage rates for the oxide SAG mill are significantly higher at the fine end of the charge particle size distribution for the test where the SAG mill was run at 75% critical speed which is consistent with the observations made with respect to the amount of fine material generated across the SAG mill.

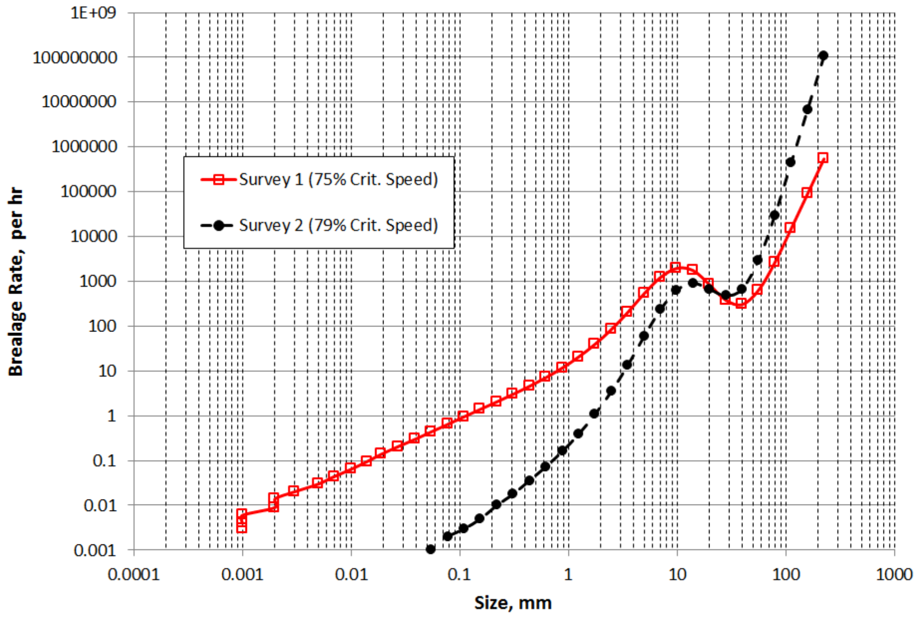

Figure 6 - Breakage rates for the Oxide SAG mill from the survey data showing the effect of mill speed

In addition, Survey 1 produced a marginally finer circuit product compared to Survey 2, despite drawing a coarser feed (Figure 5). The higher speed in Survey 2 increased coarse particle breakage in the SAG mill although there was no increase in throughput was realised as should be expected under aggressive breakage conditions.

Although higher throughputs are normally obtained at lower volumetric charge levels the authors have encountered situations where throughput benefits are achieved at higher fillings particularly for soft ore which invariably tends to contain high amounts of sub grate material. The current results suggest that the oxide circuit performs better in terms of both throughput and grind at the lower speed setting where charge motion is predominantly cascading. This behaviour is consistent with the response of soft material to abrasion breakage conditions which are favoured by high volumetric filling conditions.

Mixed circuit

The mixed plant was operated with a volumetric filling of 21.9% for the first test and 37.2% for the second test. Higher throughputs were obtained in the test conducted at a filling level of 37.2%. A 14% increase in throughput was experienced by changing the SAG volumetric filling from 21.9% to 37%. The significant change in throughput seems to suggest that for low abrasion resistance material, operating at high loads is beneficial (Table 1).

Although the feed particle size distribution for the test conducted at 37.2% volumetric filling was coarser, the product from the primary mill was significantly finer than the product obtained from the 21.9% filling degree test as shown in Figure 7. The final product grind coarsened slightly most probably due to the operation of the ball mill although the product was still within the specifications for the downstream flotation process requirements. In addition, the increase in tonnage observed in the high volumetric filling degree resulted in a net reduction in specific energy consumption.

Overall, the results appear to suggest that conditions in the SAG mill were largely responsible for changes to both grind and throughput experienced at the higher filling degree. The SAG mill produced roughly twice the amount of new fine material (<1mm) despite drawing a coarser feed for the high SAG mill volumetric filling test compared to the lower one (Figure 7). This is similar to the response of oxide ore but is in contrast to the response of sulphide ore discussed in the preceding sections of this study.

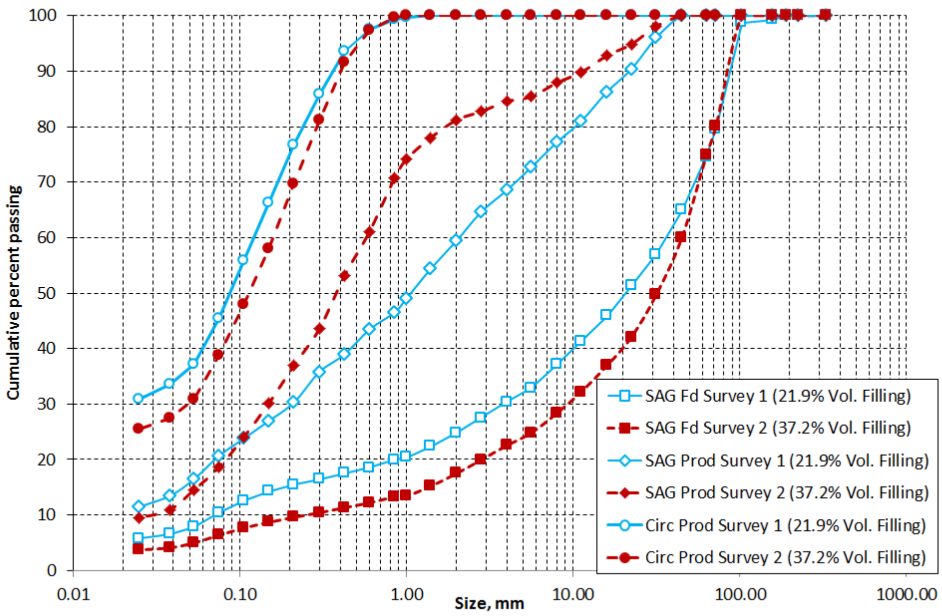

Figure 7 - Comparison of particle size distributions of some key streams in the mixed circuit surveys

The origin of mixed ore in the Kansanshi ore body is such that the ore retains some characteristics of both the sulphide and oxide ores. Ore characterisation tests performed in this study established that the impact resistance of mixed ore is in the same category as the sulphide ore, while the abrasion resistance is characterised as transitional, though with a strong bias towards the ‘soft’ demeanour of the oxide ore (Table 1). It appears therefore that the abrasion properties of the oxide ore component dominated the behaviour of the mixed ore milled in these tests. Hence for this test consignment, high throughputs occur at high volumetric filling levels where low energy (abrasion) breakage is prevalent.

However, it is likely that the proportion of either sulphide or oxide component in the mixed ore composite will vary appreciably depending on the execution of the mining activities, leading to possible fluctuations in the composition of the mixed ore blend. The modelling work done as part of this study will assist in defining operating set-points for such conditions.

CONCLUSIONS

The three ore types making up the Kansanshi ore body exhibit distinct strength properties that require different operational approaches for efficient size reduction. This study provided insights into the application of different operational philosophies in dealing with variability found in the single ore body. Ore characterisation tests performed on the Kansanshi ores rated the sulphide ore as the most competent while oxide ore was adjudged the least competent. The mixed ore displayed transitional properties characteristic of the sulphide and oxide constitutes of the mixed ore blend.

At the operational level, the average specific energy consumption associated with each circuit reflects the characteristic strength hierarchy observed amongst the ore types, while at the planning level the differences in installed power between the circuits shows the impact of the reserve variability on process design decisions. From the analysis of a series of surveys conducted on the three circuits, this study has shown that in addition to influencing equipment selection and design, operating strategies are profoundly influenced by the breakage characteristics of the ore processed.

The survey results indicate that for soft ores there is advantage in operating with high volumetric filling degrees in the SAG mill. Besides both being characterised as soft with respect to abrasion resistance, the mixed and oxide ores responded similarly to changes in SAG mill filling during operation. The mixed ore circuit experienced a 14% increase in throughput when the SAG volumetric filling degree changed from 21.9% to 37.2%, with little change in grind. Similarly, a 2% increase in volumetric filling for the oxide SAG mill, though small in comparison, lead to a noticeable increase in throughput accompanied by a 10% increase in sub 75µm fraction in the circuit product. However, for the medium to hard ore it appears there is advantage in operating the SAG mill with low volumetric filling degrees. When the volumetric filling of the sulphide SAG mill was reduced from 33.7% to 26.6% the circuit throughput increased by 20%, though the final product grind coarsened as shown by a 16% decrease in sub 75µm in the circuit product.

Thus, the filling degrees at which the relatively softer ores perform well were around 32 – 37 % while the harder ore performed well around 26% volumetric filling degree in the SAG mill. It should be noted though that the mixed and oxide ore feed materials contained considerably more fine material compared to the sulphide feed. This is expected because less competent ores generally experience higher fragmentation during handling and therefore exhibit higher percentages of fine material.

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