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ABSTRACT 578

Geometallurgy: new accurate testwork to meet required accuracies of mining project development

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ABSTRACT

The main purpose of geometallurgy is to improve the mine planning by mapping hardness and throughput into the mine block model using geostatistics to eliminate the large production fluctuations caused by the ore hardness variability coming from different parts of the pit. However, not all grinding testwork available commercially can be applied to geometallurgy because of large amount of sample required and the associated cost per test. Geometallurgy is now being used in designing grinding mill but as the mining project progress, the accuracy of engineering must improve from 30-35% during the scoping study to 10-15% at the bankable feasibility stage and less than 5% for Engineering Procurement and Construction Management.

For SAG milling, the SAG Variability Test (SVT) is an abbreviated version of the standard SAGDesign test developed for this geometallurgical need. The same amount of ore than the original test is ground for three cycles into an open batch SAG test and then the SAG pinion energy is predicted to the standard end point of 80% passing 1.7 mm. For ball milling, a Bond Variability Test (BVT) was also developed using the SAG ground ore from the SVT. The Bond ball mill grindability (Gpb), corresponding to the average of the net grams per revolution from the last three cycles of the Bond test, is also predicted from the third cycle.

The relative error for both the predicted SAG ore hardness (W_{SVT}) and Bond Work Index on SAG Variability ground ore (S_v-BVI), in kWh/t, averaged 5.5% and 3.8% respectively compared to the SAGDesign testwork values and are within 7% and 10% respectively from plant benchmark and within 7% from the samples sent to all partner laboratories. Both tests can be continued to measure the true hardness necessary for mill sizing. This article discusses the development of these two new tests, SVT and BVT, their potential use and accuracies in any geometallurgical program.

INTRODUCTION

Comminution testwork is conducted to mitigate risks associated with the selection and design of a grinding circuit to ensure that the project generates the necessary cash flow during the payback period. With geometallurgy, the mine planning is thus optimized by mapping hardness and forecasting throughput into the mine block model using geostatistics to achieve design tonnage over the life of mine of the deposit and eliminate the large throughput fluctuations caused by the ore hardness variability. From the available commercialized grinding tests, some are simply not applicable to geometallurgy because of the larger number of samples required and their associated cost. New tests or simplified procedures were developed to measure the ore hardness quickly and cost effectively like the SPI or the SMC test for SAG milling and the Modified Bond test or the JK Bond Ball Lite (JK BBL) for ball milling.

An understanding of the implications of the testwork methods and data interpretation is required to effectively moderate the risks. Not only the number of required samples depends on the grinding testwork chosen and increases during each progressing stage of a mining project (Meadows, Scinto & Starkey, 2011) but the estimate and relevant testwork need also to be more accurate (Lunt, Ritchie & Fleay, 1997 and Scott & Johnston, 2002): 30-35% for the FEL Phase I (scoping or conceptual), 20-25% for Phase II (preliminary economic assessment and pre-feasibility), 10-15% for Phase III (bankable feasibility) and less than 5% for Engineering, Procurement and Construction Management (definitive).

The purpose of this paper is to introduce a new variability or geometallurgical test based from the SAGDesign grinding testwork as an effective solution to mitigate the risk of mill selection and design of a grinding circuit as well as to production forecasting that will meet the accuracy requirement of the progressing development stage of any mining project. The SAGDesign test is an open batch SAG test to grind the ore progressively in stage (or cycle) to 80% passing 1.7 mm in 6 to 8 cycles in general, followed with a locked cycle Bond test performed on the SAG ground product from that SAG test to the final grind product as defined by the standard Bond test. The accuracy of the SAGDesign testwork and the difference between the standard Bond test on crushed feed and SAG ground ore versus were already discussed in many papers exceeding the scope of this paper (Starkey & Larby, 2012, Starkey & Scinto, 2010, Starkey, Hindstorm & Nadasdy, 2006 and Starkey & Meadows, 2007).

SAG VARIABILITY TEST (SVT)

An initial model, not published except commercially, was developed to predict the number of revolutions of the non-linear portion of the SAG grind curve from 60% to the endpoint of 80% passing 1.7 mm of the SAGDesign test by conducting the first part test only to 60% passing 1.7 mm. However, the number of samples used to build the model was reduced to 620 from the 792 SAGDesign test results, or 78% of the database at the time, due to the passing of the initial feed size limited to be less than 20% minus 1.7 mm.

SAG Test Cycles Analysis

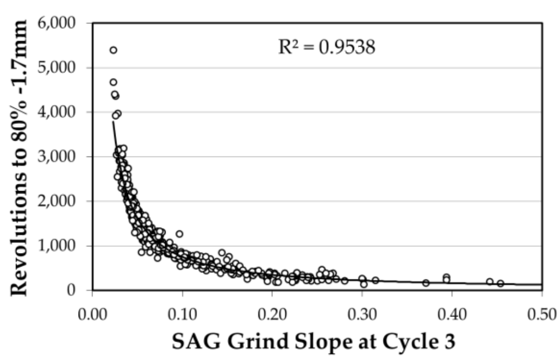
Instead, the number of cycles during the first part of the test, corresponding to the the linear portion of the SAG grind curve up to 60% minus 1.7 mm, was investigated using a multiple linear regression with the following independent variables: the SAG grinding curve slope, the average passing per cycle and the initial passing 1.7 mm of the SAG feed. The main predictor variable, the SAG grinding curve slope, was found to have a non-linear relationship with the number of revolutions required to achieve the end point of 80% passing 1.7 mm of the SAGDesign test with a low variance as shown in Figure 1 (Brissette et al., 2014). A logarithmic transformation was used to linearize the data.

Regression Modeling and Analysis Summary

Table 1 summarizes the regression and the ANOVA analysis after three cycles with a model refined by excluding standard residuals higher than three standard deviations (3σ) but included in the calculation of the model's error. 11 outliers were the effect of the initial SAG mill feed finer than 40% passing 1.7 mm and 13 outliers had quality control notes without affecting the final W_{SAG} hardness value. The population considered for the regression modelling was 764 out of a total of 796 or about 96% of the SAGDesign database. The new model explains more than 98% of the variability observed in the measured W_{SAG} hardness, as depicted in Figure 2, with an absolute relative error (RE) averaging 5.4%. The model is extremely significant because of a high Fisher number with a larger population number and low probability value. The residuals did not follow any pattern and were following a normal distribution with constant variance.

Table 1 Regression ANOVA and Statistical Summary after three cycles of the SAG test

Cycle	Std. Res. > 3σ	SSR	SSE	RSEE	R^2	F	p	% of N	Avg Abs RE
3	6	318 315 583	5 890 772	6.6%	0.982	6 827	0	96.0%	5.4%



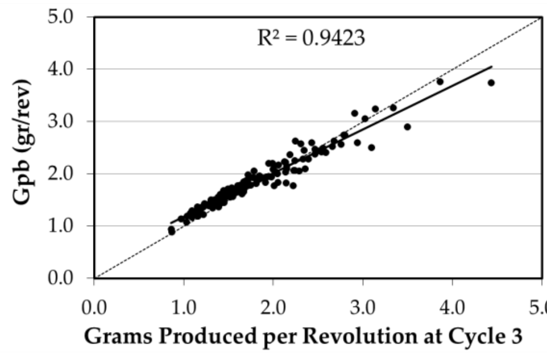


Figure 1 Relationship and Variance of the Main Predictors after 3 Cycles from the SAG and Bond test database

BOND VARIABILITY TEST (BVT)

Bond Test Cycles Analysis

For the Bond test on SAG ground ore, the net grams produced per revolution during each cycle was investigated as the main variable. It was found that the number of cycles can be reduced to three cycles as initially suggested by others (Jankovic et al., 1997) and used by JK BBL (Kojovic & Walters, 2012) with a R^2 of about 95% using a simple linear regression model, as demonstrated in Figure 1 for a closing screen of 150 microns, which adjust the net grams of undersize produced per revolution to match the ball mill grindability (Gpb), corresponding to the unity line (Brissette et al., 2014). It is to be noted that the values more than 2 gr/rev represent softer ore and have more variability on that closing screen size.

Regression Modeling and Analysis Summary

The Bond cycles in the database was analysed for each of the following closing screen size: 75, 106, 150 and 212 microns. Some Bond grindability tests in S&A database were conducted at 53 and 300 microns but the number of samples tested was below the minimum number of 30 observations required to develop a regression model. It was found that the Bond test results during the SAGDesign testing followed different trends for these four closing screen sizes. Thus, four models were regressed.

Table 2 Regression and ANOVA Summary at Four Different Closing Screens

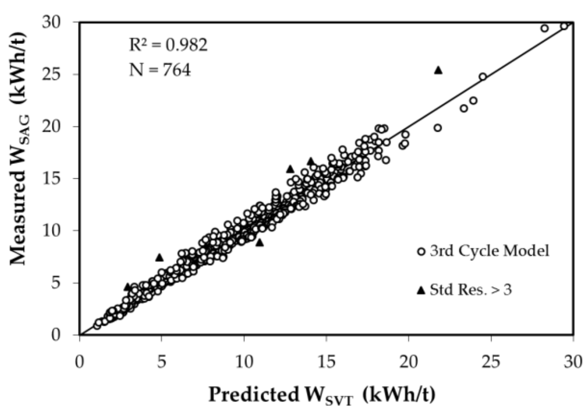
Screen	N	Std. Res. > 3σ	Outliers	SSR	SSE	RSEE	R^2	F	p	% of N
75 μm	46	0	(3)	6.837	0.222	5.3%	0.969	1 354	1.1^{E}-34	100%
106 μm	339	9	7	41.077	1.572	4.7%	0.963	8 807	1.3^{E}-243	95.7%

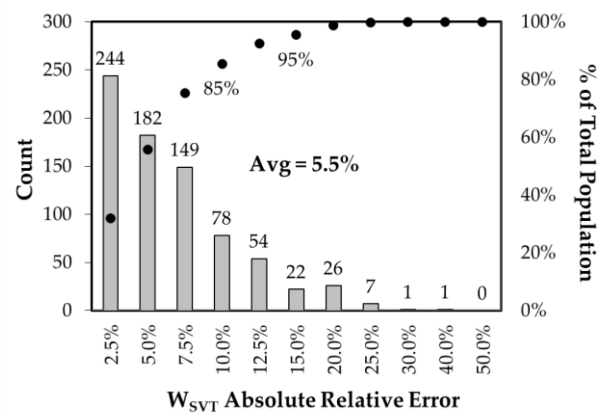
150 μm	153	4	4	28.170	1.293	5.2%	0.956	3 289	2.1E-104	95.0%
212 μm	200	8	2	96.578	4.446	6.0%	0.956	4 301	3.0E-136	95.5%

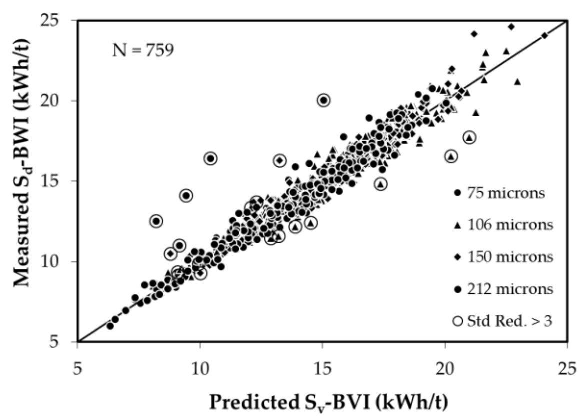
Table 2 summarized the regression and ANOVA analysis. The regression model was refined by excluding the standard residuals above three standard deviations. The grams produced per revolution at the third cycle were explaining more than 95% of the Gpb variability ($R^2 > 0.95$). The relative standard error of estimates (RSEE) was indicating a low variance of the prediction around the regression line (< 6%). Finally, the models developed for each closing screen are highly significant due to their high Fisher number (F) and extremely low probability (p) values. Outliers can be explained either by very soft ores, finer feed size (less than 700 microns) or instability during the first cycles. At 75 μm closing screen, the outliers were the crushed BWI as per Bond standard procedures. Surprisingly, the BVT model fitted those real BWI values.

SVT-BVT MODEL ACCURACY AND TESTWORK VALIDATION

From Figure 2, the predicted SAG pinion energy obtained from the SVT, called W_{SVT}, has a low variance around the regression line. 95% of their values have a relative error less than 15% compared to the measured W_{SAG}, averaging 5.5%. For the predicted Bond BWI or the Bond Variability Index on SAG Variability ground ore, referred as S_v-BVI, 98% of the values have a relative error within 15% compared to the measured S_d-BWI, averaging 3.8%. It has the same order of magnitude reported by the JK BBL (Kojovic & Walters, 2012).




Count
% of Total Population
Avg = 5.5%
244
182
149
78
54
22
26
7
1
1
0
85%
95%
2.5%
5.0%
7.5%
10.0%
12.5%
15.0%
20.0%
25.0%
30.0%
40.0%
50.0%
W$_{SVT}$ Absolute Relative Error


N = 759
Measured S$_d$-BWI (kWh/t)
Predicted S$_v$-BVI (kWh/t)
75 microns
106 microns
150 microns
212 microns
Std Red. > 3

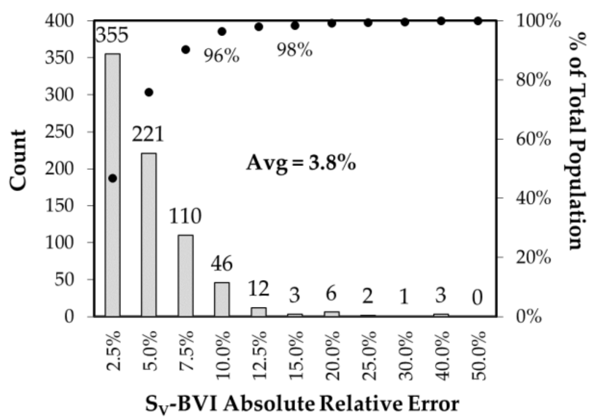


Figure 2 Accuracy of SVT and BVT compared to the SAGDesign Test Results

To validate the model, SVTs were performed each followed by a BVT on leftover samples where the SAGDesign testwork results were already available for both the SAG hardness and Bond BWI on SAG ground ore. The testwork results are summarized in Table 3.

Table 3 New SVT and BVT Model Accuracy versus Measured SAGDesign Results

Test	W_{SAG}	W_{SVT}	Abs. Rel.	S_d-BWI	S_v-BVI	Abs. Rel.	Sd-BWI Size (µm)		S_v-BVI Size (µm)	
No	kWh/t	kWh/t	Error (%)	kWh/t	kWh/t	Error (%)	F80	P80	F80	P80
1	11.50	11.72	1.8%	15.83	15.66	-1.1%	1,175	159	1,917	153
2	7.06	7.68	8.8%	13.88	13.42	-3.3%	1,410	184	1,952	148
3	11.00	11.34	3.2%	12.46	13.22	6.0%	1,427	60	1,866	58
4	12.08	12.14	0.5%	17.83	16.91	-5.1%	1,246	161	1,583	155
Avg			3.6%			3.9%				

The average of the absolute relative error of the W_{SVT} versus the W_{SAG} is 3.6% and 3.9% for the S_v-BVI when compared to the S_d-BWI of the full SAGDesign test results. It is to be noted that a manipulation error occurred during the SVT of sample no 2, which may have affected the SAG hardness measurement.

As anticipated, the product size from the SVT after 3 cycles, corresponding to the Bond feed, is much coarser than the product of SAGDesign test brought to 80% minus 1.7 mm. Astonishingly, the feed size did not affect the result of the S_v-BVI model versus the measured S_d-BWI values.

SVT-BVT VERSUS SAGDESIGN TEST ACCURACY

The main advantage of developing the SAG and Bond variability models from the SAGDesign database is that SAG hardness and Bond Work Index can be predicted from the third cycle of any completed SAGDesign test.

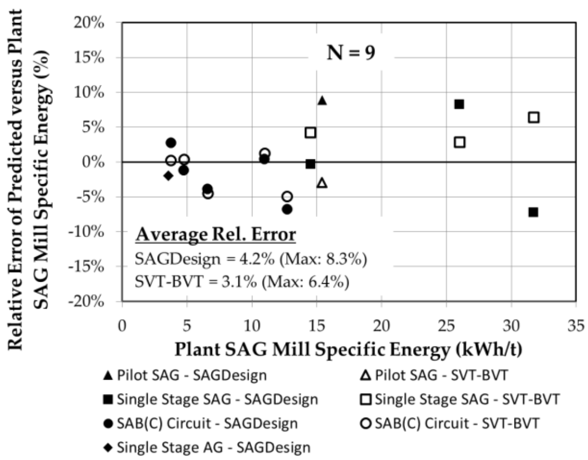
It was already demonstrated that the relative standard deviation (RSD), or the coefficient of variation (CoV) as used by JK, of the W_{SAG} measured by the SAGDesign test on the same ore samples sent to the 8 partner laboratories was 3.1% with a maximum relative error of 4.6% as reproduced in Table 4 (Starkey & Larbi, 2012). When applying the SVT model on the third cycle of the SAG test, the RSD of the W_{SVT} is 4.2% with a maximum relative error of 6.9%. For the Bond test on SAG ground ore, the RSD of the S_d-BWI was 5.7% with a maximum relative error of 8.7%. When applying the BVT model on the third cycle of the Bond test, the RSD of the Sv-BVI is 6.3% with a maximum relative error of 10%.

The W_{SVT} is 10.8% above the W_{SAG} value and the Sv-BVI is 8.7% above the measured S_d-BWI. All values are being between 10 and 15% within the bankable feasibility study requirement.

Table 4 SVT and BVT Model versus SAGDesign Test Accuracy

Lab No	W_{SAG} kWh/t	Abs. Rel. Error (%)	W_{SVT} kWh/t	Abs. Rel. Error (%)	S_d-BWI kWh/t	Abs. Rel. Error (%)	S_v-BVI kWh/t	Abs. Rel. Error (%)
A	7.30	1.0%	7.79	4.7%	8.88	8.7%	9.61	9.1%
B	7.71	4.6%	8.49	3.8%	10.00	2.8%	10.93	3.4%
C	7.68	4.1%	8.44	3.2%	10.52	8.1%	10.24	3.1%
D	7.17	2.9%	8.13	0.5%	9.76	0.3%	11.02	4.2%
E	7.28	1.3%	8.05	1.5%	9.42	3.2%	10.97	3.7%
F	7.17	2.8%	7.87	3.7%	10.32	6.1%	11.63	10.0%
G	7.18	2.7%	7.88	3.6%	9.19	5.6%	10.21	3.5%
H	7.52	2.0%	8.74	6.9%	9.75	0.2%	9.98	5.6%
Average	7.38	2.7%	8.17	3.5%	9.73	4.4%	10.57	5.2%
RSD (Max)	3.1%	(4.6%)	4.2%	(6.9%)	5.7%	(8.7%)	6.3%	(10.0%)

Figure 5 with the values tabulated in Table 4 shows the accuracy of both SAGDesign and SVT-BVT testwork versus plant benchmarking. For SAG milling, the SAG specific energy is mainly predicted within 5%, averaging 3.1%, except for single stage SAG milling below 100 microns (> 25 kWh/t) which are within 10%. For ball milling, the ball mill specific energy is predicted within 7% from the plant, averaging 5.8%. Regardless, all the predicted and measured values were within 10% of the plant values, meeting the accuracy criteria of any bankable feasibility study. For AG milling, the SAGDesign testwork was performed with a closing screen of 850 microns for the SAG test and 300 microns for the Bond which were not covered during the modelling of the SVT-BVT testwork.



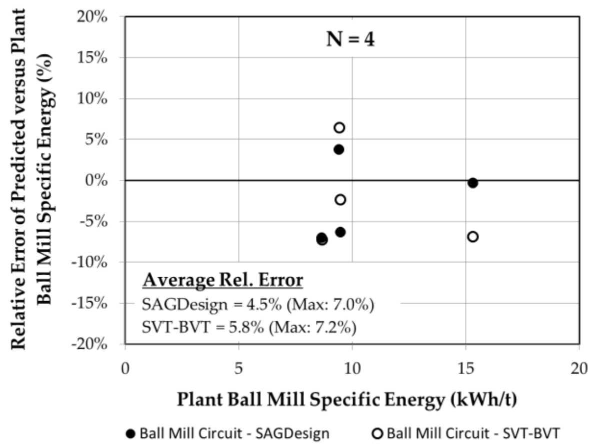


Figure 3 Accuracy of the SVT-BVT compared to the SAGDesign Test Results from Plant Benchmarking

Table 4 SVT and BVT Model versus SAGDesign Test Accuracy

Project No	Grinding Circuit	Observed Plant SAG kWh/t	Calculated SAGDesign kWh/t (RE)	Predicted SVT-BVT kWh/t (RE)	Observed Plant BM kWh/t	Calculated SAGDesign kWh/t (RE)	Predicted SVT-BVT kWh/t (RE)
1	Pilot	15.40	16.77 (+8.9%)	14.95 (-3.0%)	N/A		
2	SS SAG	14.52	14.48 (-0.3%)	15.14 (+4.3%)	N/A		
3	SS SAG	26.00	28.15 (+8.3%)	26.74 (+2.9%)	N/A		
4	SS SAG	31.71	29.42 (-7.2%)	33.75 (+6.4%)	N/A		
5	SS AG	3.56	3.50 (-1.9%)	N/A	N/A		
6	SAB	3.75	3.85 (+2.7%)	3.76 (+0.3%)	8.66	8.05 (-7.0%)	8.03 (-7.2%)
7	SAC	10.96	11.01 (+0.4%)	11.09 (+1.2%)	15.30	15.25 (-0.3%)	14.25 (-6.8%)
8	SAB	4.74	4.68 (-1.2%)	4.76 (+0.4%)	9.47	8.88 (-6.3%)	9.25 (-2.3%)
9	SAB	12.71	11.86 (-6.7%)	12.09 (-4.9%)	9.41	9.77 (+3.8%)	10.02 (+6.5%)
10	SABC	6.58	6.32 (-3.9%)	6.28 (-4.5%)	N/A		

TESTWORK ACCURACY VERSUS PROJECT REQUIREMENT

Table 5 summarizes the recommended number of samples for each stage of the project (Meadows, Scinto & Starkey, 2011). Composite samples are used for design and point hardness samples for geometallurgy but drill core size shall not be ignored when selecting grinding testwork. For the full version of the grinding testwork, used for design and optimization purposes, the accuracy is based on the relative standard deviation because the error is based on repeated test on the same sample. For the abbreviated version of the test, used for geometallurgical and production forecasting purposes, the accuracy is rather based on the relative error because it is compared to the measurement from the full version of the test performed on the same sample and covering the full range of ore hardness or competency.

Table 5 Grinding Testwork Samples Requirement and Accuracy versus Projects Requirements

Project & Accuracy Design Testwork	Scoping 30-35%	PEA 20-25%	PFS 20-25%	FS 10-15%	EPC < 5%	Drill Core Size Req'd	Qty kg	RSD	Max. Error
SAGDesign:	1	3	10	25	50	Half NQ	15		
SAG						or Full AQ		3.1%	4.6%
Bond								5.7%	8.7%
JK DWT	1	6	20	50	100	Full HQ	100	4.2-7%	14%
JK RBT	1	6	20	50	100	Full NQ	100	3.9%	12%
Bond Suite	3	12	40	100	200		50		
CWI+						Full NQ		40%	>100%
RWI+BWI						Full AQ		4-6.2%	10-15%
Geomet Testwork								**Average Rel. Error**	
SVT +	1	6	20	50	100	Half NQ	25	5.5% vs W_{SAG}	
BVT						or Full AQ		3.8% vs S_d-BWI	
SMC +	3	12	40	100	200	Full AQ	25	12.7% vs DWT	
JK BBL								4.1% vs Bond	
SPI +	3	12	40	100	200	Half NQ	15	Not Published	
MBWI						or Full AQ			

For testwork used in design, the accuracy of the JK drop-weigh test varies between 4.2% and 7% (Bailey et al., 2009, Stark, Perkins & Napier-Munn, 2008 and Shi & Kojovic, 2011) while the JK RBT is slightly more accurate at 3.9%. The Bond ball mill grindability test accuracy can be up to 10% between different laboratories but within 3.4 to 6.2% if performed in the same lab (Angove & Dunne, 1997, Mosher & Tague, 2001 and Kaya, 2001), which is in the range obtained with the Bond Work Index on SAG ground. The impact Crusher Work Index (CWI) was measured about 40% but with insufficient result to draw valid statistical conclusion while the Bond rod mill grindability accuracy was less than the Bond ball mill WI (Angove & Dunne, 1997).

For testwork used in geometallurgy, although the relative standard deviation of the SMC had been reported to be 3.9% on the same sample from different laboratories (Morrell, 2009), the relative error is averaging 12.7% when compared to the JK DWT at different hardnesses when both are performed on the same sample (Brissette et al, 2014). The accuracy of the SPI test has never published but when the ore is harder than 150 minutes, small difference in the feed size or the ore competency can lead to very large differences in the test result (Amelunxen, Berrios & Rodriguez, 2014). The relationship between the standard Bond and the modified Bond test was reported to be highly correlated (Kuyvenhoven, McKen & Velasquez, 2004)

CONCLUSION

The SAG Variability Test (SVT) can predict the measured W_{SAG} by performing three grinding cycles from the SAG portion of the SAGDesign test only. 95% of the predicted values have less than 15% error, averaging 5.4%. The SVT required the same amount of material of the SAGDesign test about 8-10 kg of ore. The Bond Variability Test (BVT) can predict the measured S_d-BWI using a regression model for each screen size by performing three locked cycles only. 98% of the predicted S_v-BVI values have less than 15% error, averaging 3.8%. Compared to plant benchmark, both the W_{SVT} and S_v-BVI were predicted within 7% and 10% respectively.

Two new tests procedure were developed using the SAGDesign methodology for any geometallurgical study and meet the accuracy required from conceptual (25-30% error) up to bankable feasibility (10-15% error) or to EPMC (< 5% error) when completed to the full SAGDesign test. The total cost of both tests is reduced by 55% compared the cost of the full test.

It opens the door to a new approaches for geometallurgical studies where accuracy of the hardness measurement can be increased by performing one cycle at a time up using only one sample, without the need to extract and ship additional core, to the full SAGDesign test in order to meet the increasing accuracy requirement of any mining project stage from order of magnitude to the definitive stage.

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