Evaluating the Additivity of Different Lithologies in Geometallurgical Tests of Copper-Gold Ore Flotation

Flavio Moura[1,2], Gerando Santos[2], Thais Fonseca[2], Douglas Mazzinghy[1]

1. *Lundin Mining, Brazil*
2. *Federal University of Minas Gerais (UFMG), Brazil*

ABSTRACT

Flotation tests for geometallurgical modeling aim to estimate the recovery of a given block. However, the beneficiation plant is normally fed with a mixture of different blocks (lithologies). The technical literature describes the recovery of flotation tests as a non-additive variable, which makes it difficult to use classical geostatistical models (kriging) to estimate the recovery. In this work, three lithologies were selected, called BTOS, QRST and GNS, with physical, chemical and mineralogical characteristics distinct from the Chapada Mine. The three lithologies were mixed in different proportions in order to verify the additive effect of metallurgical recovery. Through the bench flotation tests, it was possible to identify that the metallurgical recoveries for copper and gold do not present an additive behavior. Furthermore, mathematical prediction models were proposed for the recovery variable, based on the obtained experimental results.

INTRODUCTION

The ores are formed by particles of different minerals, some represent mineral species to be concentrated, mineral ore, and others, of lesser value, make up the gangue to be discarded (LUZ *et al*, 2004). One of the most used concentration processes in the mineral industry is flotation, applied to the processing of different ores. According to Baltar (2008), the differentiating property of flotation is the hydrophobicity of each mineral, indirectly measured by the contact angle between the particle and the drop of air, formed from the deposition of the drop on a flat surface of the immersed solid (mineral) in the water.

This work aims to evaluate the additive character of metallurgical recovery in mixtures of three lithologies with different characteristics. As a result, there is a comparison of the results of real and calculated metallurgical recovery adopting the additive character, from the different mixtures of the three lithologies studied. Finally, mathematical models were proposed to predict the metallurgical recovery of copper and gold.

METHODOLOGY

For the development of this work, three distinct lithologies were used, called BTOS, GNS and QSRT. The ores samples collected at the mining fronts were initially classified into coarse, intermediate and fine materials, then adopting the cutting meshes of 63mm and 25mm. Next, equal parts of each product (coarse, intermediate and fine) were combined in order to avoid any accumulation bias of certain minerals in coarse, intermediate and fine fractions.

Then, the samples were crushed below 3.36 mm through a primary crushing circuit in a jaw crusher, and secondary crushing in a roller crusher, in a closed circuit, thus guaranteeing the desired granulometry. With the crushed material, the samples were homogenized and quartered by the elongated pile method in 1.6 kg aliquots, obtaining three aliquots of each lithology as the head sample of the tests, in addition to approximately 2 aliquots for the grinding and 13 samples for flotation, for each lithology.

The first test carried out consisted of defining the grinding time for each pure sample (100% BTOS, 100% QSRT and 100% GNS), in order to reach a P80 of approximately 300 microns, granulometry adopted in the processing plant of Mina Chapada. For this, two grinding tests were carried out with different times for 1.6 kg samples of each lithology, which will be presented in the results. For each particle size distribution of the product obtained, through sieving in the meshes of 10, 20, 35, 50, 70, 100, 150, 200, 270 and 400 mesh, a P80 value was then calculated. Then a graph was plotted correlating the P80 values with the milling time and then defining an equation that correlates these values. Through this equation, the time required to adapt each sample to the desired P80 (300 microns) is calculated. The parameters adopted for the grinding tests are shown in Table 1:

Table 1 Parameters of grinding tests

Parameter	Unit	Value
Internal diameter	mm	220
Length	mm	330
Rotation	rpm	60
% of Critical Speed	%	66.5
Bars - Smaller Size - Quantity	-	18
Bars - Smaller Size - Diameter	mm	11
Bars - Smaller Size - Length	mm	290
Bars Mid-Size - Quantity	-	5
Bars Mid-Size- Diameter	mm	16
Bars Mid-Size - Length	mm	280
Bars - Larger Size - Quantity	-	10
Bars - Larger Size - Diameter	mm	18
Bars - Larger Size - Length	mm	290
% of solids	%	61.5

With the grinding time defined, the validation of the result was carried out by means of the repetition of the grinding tests in the found times and granulometric analysis in the meshes mentioned above. The P80 result found for each lithology was compared to that obtained by the equation, so that the difference between them was not greater than 5%. Finally, the comminuted material was filtered and dried. This procedure was performed for the three lithologies.

After defining and validating the grinding times and adopting the parameters shown in Table 1, grindingtests were carried out with 1.6 kg samples of each lithology, previously quartered, until the mass obtained was approximately 20 kg, guaranteeing, thus, the availability of sufficient mass of P_{80} in the granulometry of 300 microns to carry out the flotation tests.

With the samples of each lithology obtained in the milling, the quartering was carried out using the elongated pile method, separating samples with the masses of 1.6 kg, 1.2 kg, 0.8 kg and 0.4 kg to compose the samples blended from flotation tests, for each lithology. The composition of the samples used in this work is presented in Table 2.

Table 2 Composition of Samples

Sample		1	2	3	4	5	6	7	8	9	10	11	12	13
Mass composition (%)	% BTOS	100	0	0	75	50	25	75	50	25	0	0	0	33,33
	% QSRT	0	100	0	25	50	75	0	0	0	75	50	25	33,33
	% GNS	0	0	100	0	0	0	25	50	75	25	50	75	33,34

Tests to determine the metallurgical recovery of copper and gold were carried out using bench flotation tests, in triplicate, in order to estimate test errors. The parameters adopted are shown in Table 3:

Table 3 Parameters of flotation tests

Parameters	Unidade	Valor
pH	-	10.5
Conditioning time	s	90
Flotation time	s	360
P_{80}	µm	300
Dry mass per test	kg	1.6
% of solids	%	33
Dosage - PAX	g/t	15
Dosage - Dithiophosphate	g/t	20
Dosage - DF400	g/t	20
Dosage - MIBC	g/t	20

For each test performed, a sample of concentrate and tailing was obtained, which were subjected to copper analysis by atomic absorption and gold analysis by the Fire Assay method. Finally, through the results of the flotation tests, a comparison was made of the experimental results of metallurgical recovery of the sample mixtures in different proportions of blends with the theoretical values of recovery, obtained through the sum of the contributions of each part, based on those of pure sample results. Furthermore, mineralogical analyzes were performed, in duplicate, by the Mineral Liberation Analyzer (MLA), obtaining the modal mineralogy of samples AM-01 and AM-02 from the GNS lithology, AM-03 and AM-04 from the QSRT and AM lithology -05 and AM-06 of the BTOS lithology, which were used to propose the mathematical models.

RESULTS AND DISCUSSION

The grinding curves were constructed by comparing the two tests. For BTOS, QSRT and GNS lithology, the defined times were 4 and 6 minutes, 6 and 10 minutes and 6 and 10 minutes respectively. In addition to these, a joint grinding of the GNS and BTOS lithologies was carried out. Figures 1, 2, 3 and 4 show the graphs that show the relationships between the grinding time and the P80 obtained, as well as the particle size distribution of the tests.

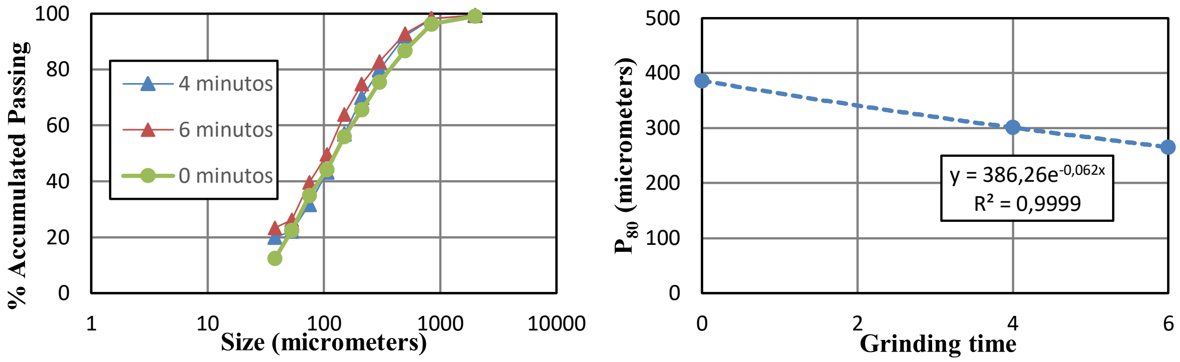


Figure 1 Particle Size Distribution and G Time versus P_{80} – BTOS

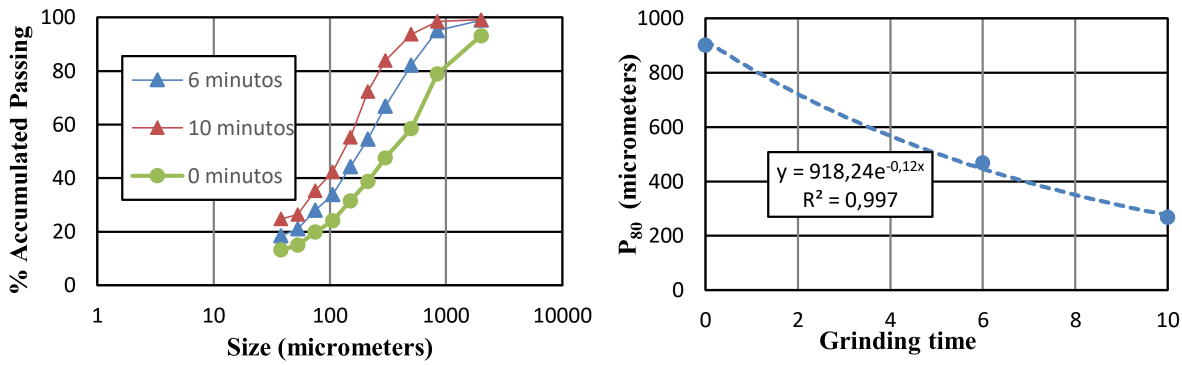


Figure 2 Particle Size Distribution and Grinding Time versus P_{80} – QSRT

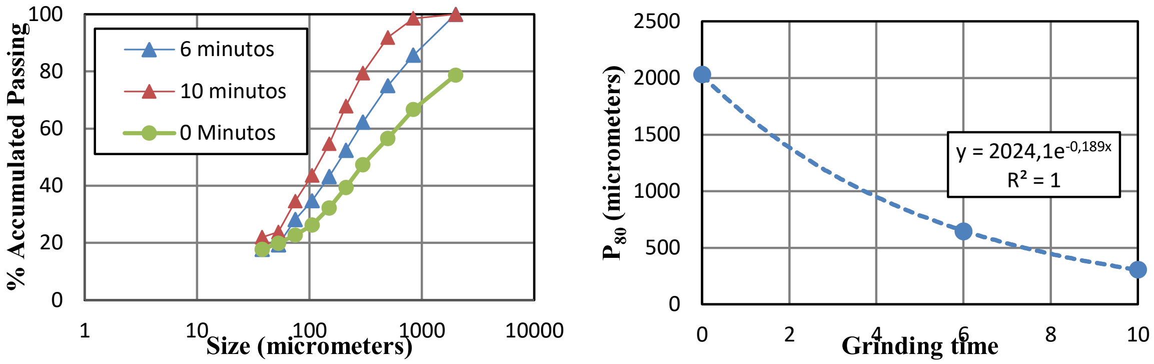


Figure 3 Particle size distribution and versus P_{80} versus Grinding Time – GNS

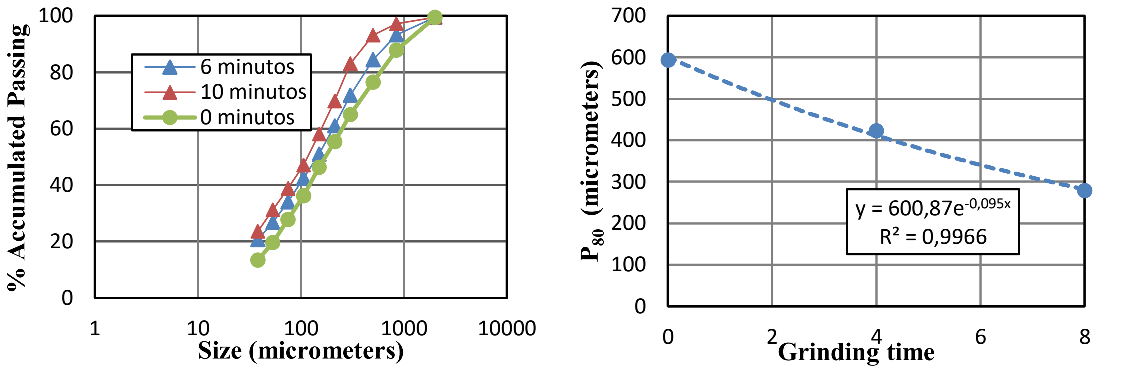


Figure 4 Particle Size Distribution and Grinding Time versus P_{80} - GNS-BTOS Joint Grinding

Validation was performed from the grinding times calculated by the curve. The results obtained by the curve and validation are presented in Table 4. It should be noted that the validation parameter was to obtain an error of less than 5.00%, which was achieved in all tests performed.

Table 4 - Validation of grinding times

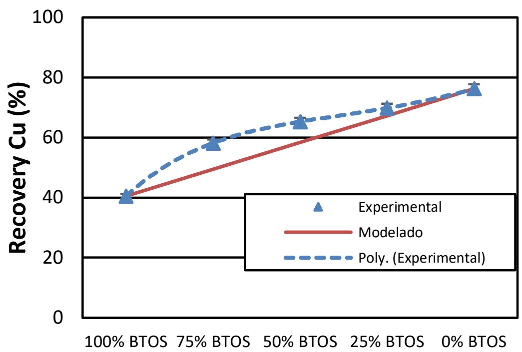
Lithologies	GNS	BTOS	QSRT	50%GNS-50%BTOS
Grinding Time (min)	10,08	4,09	9,36	7,34
Model P_{80} (microns)	300,00	300,00	300,00	300,00
Experimental P_{80} (microns)	307,70	303,70	294,40	299,6
Relative Error P_{80} (%)	2,50	1,22	1,89	0,11

Flotation tests were carried out, with the material being floated and sunk, submitted to chemical analysis of gold and copper. The values found for the real metallurgical recovery of the tests were based on the analyzed contents of concentrate and tailing. The calculated metallurgical recovery is obtained based on the relationship between the proportions of each lithology and their respective recoveries in pure samples. Table 5 presents the results obtained.

Table 5 Metallurgical recovery of composite samples

Sample		1	2	3	4	5	6	7	8	9	10	11	12	13
Mass composition (%)	**% BTOS**	100	0	0	75	50	25	75	50	25	0	0	0	33,33
	% QSRT	0	100	0	25	50	75	0	0	0	75	50	25	33,33
	% GNS	0	0	100	0	0	0	25	50	75	25	50	75	33,34
Experimental Recovery (%)	**Copper**	40,46	73,73	76,19	54,81	66,55	62,39	58,17	65,27	69,81	73,20	78,46	74,42	69,01
	Gold	39,17	40,95	54,90	43,48	48,87	43,94	46,66	49,32	51,18	42,61	51,44	51,83	48,90
Calculated Recovery (%)	**Copper**	-	-	-	48,78	57,10	65,41	49,39	58,33	67,26	74,35	74,96	75,58	63,46
	Gold	-	-	-	39,61	40,06	40,50	43,10	47,03	50,96	45,37	48,54	51,72	45,00

With regard to the metallurgical recoveries of copper and gold, comparative graphs of real and calculated recovery are presented in Figures 5, 6 and 7, which allow a better visualization of the adherence of the calculated results to the analyzed results. Insertion of the best fit trend line to the points obtained in the analysis was carried out in each graph. Figure 8 shows a comparison between calculated and actual recoveries, for the GNS-QSRT blend, grinding separately and grinding together.



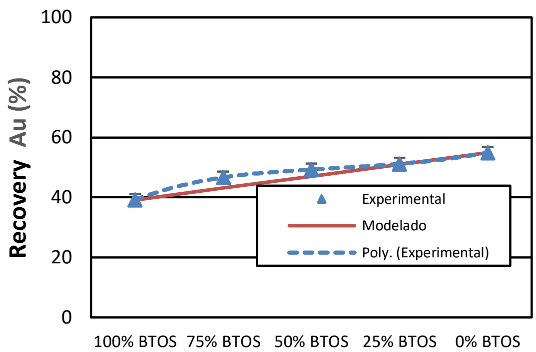


Figure 5 Metallurgical recovery of copper and gold – Blend BTOS-GNS

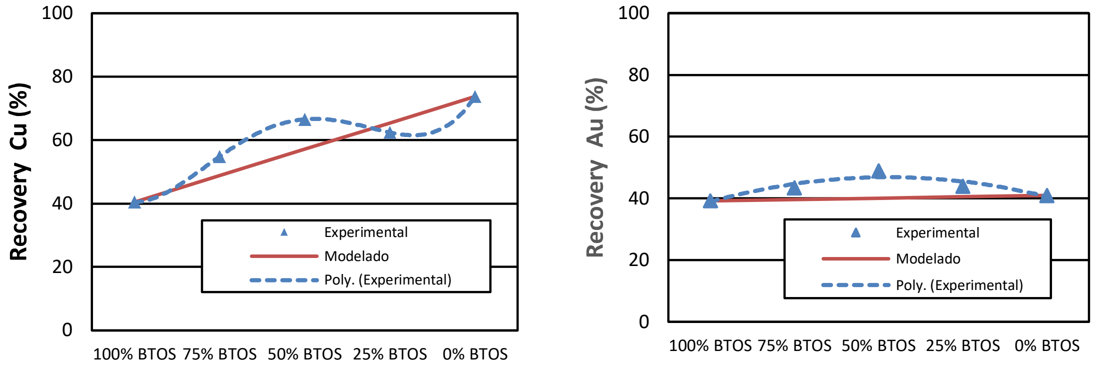


Figure 6 Metallurgical recovery of copper and gold – Blend BTOS-QSRT

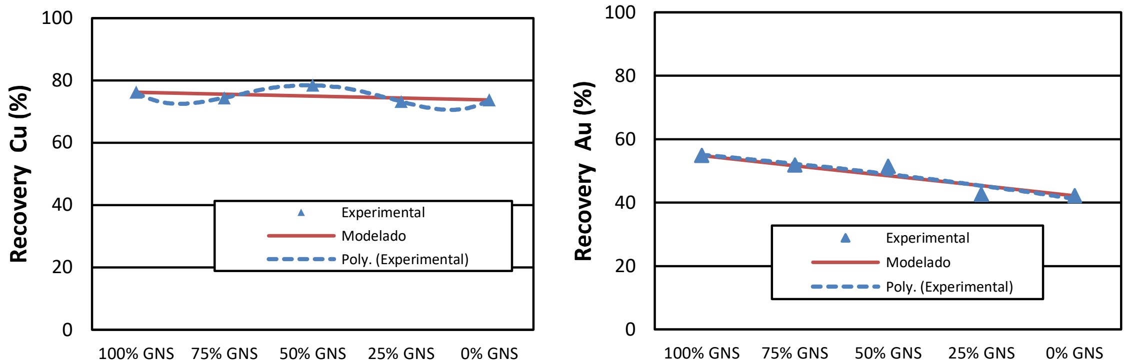
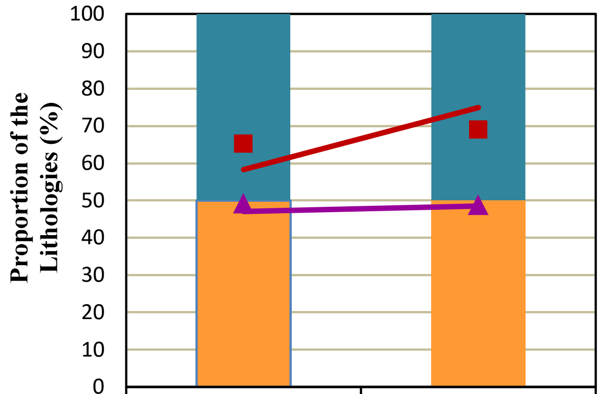


Figure 7 Metallurgical recovery of copper and gold – Blend GNS-QSRT



	Grinding separaty	Grinding together
BTOS [%]	50	50
GNS [%]	50	50
Rec Real Cu [%]	65,27	69,01
Rec Real Au [%]	49,32	48,9
Rec Calc Cu [%]	58,33	74,96
Rec Calc Au [%]	47,03	48,54

Figure 8 Metallurgical recovery of copper and gold – BTOS-GNS Blend – Separate and Together Grinding

According to the results presented, it is concluded that the metallurgical recovery is not an additive variable for the ore in question. As can be seen in the graphs above, the metallurgical recovery values are dependent on the interaction between the lithologies present in the sample, which can be seen by the adherence of the real and calculated data. In addition, it is noteworthy that the data present a certain discrepancy (absolute difference between the points), more evident for the copper values and for the BTOS-GNS and BTOS-QSRT blends, reinforcing the non-additive character of the metallurgical recovery. The real metallurgical recovery presented results closer to the calculated metallurgical recovery for ores that have close metallurgical recoveries. In order to ensure an improvement in the recovery forecast, it is recommended that ores from similar recovery be blended.

Based on all test results obtained, the variables were correlated and mathematical models were proposed for predicting the metallurgical recovery of copper and gold, for the best correlations, which are presented in Table 7, with the corresponding equation and coefficient of determination (R^2) associated.

Table 7 Proposed Mathematical Models for Copper and Gold Recovery

Blend	Suggested model	Equation	R^2
	Au Recovery - Quadratic	$\boldsymbol{Rec\ Au = -34,346x^2 + 28,958x + 40,340}$	0,96
	Cu Recovery - Linear	$\boldsymbol{Rec\ Cu = -30,978x + 73,06}$	0,85

BTOS-QSRT	Au Mineralogical - Quadratic	$Rec\ Au = -29,91 * \%BTOS * Sulphides - 55,17 * \%GNS * Pyrite + 182,12$	0,96
	Cu mineralogical - Quadratic	$Rec\ Cu = -33,17 * \%BTOS * Sulphides - 52,23 * \%GNS * Pyrite + 202,42$	0,94
BTOS-GNS	Au Recovery - Linear	$Rec\ Au = -23,318x + 59,197$	0,88
	Cu Recovery - Linear	$Rec\ Cu = -37,77x + 78,77$	0,92
	Au mineralogical - Quadratic	$Rec\ Au = -4,60 * \%BTOS * Sulphides + 0,22 * \%QSRT * Pyrite + 59,01$	0,88
	Mineralogical Cu - Quadratic	$Rec\ Cu = -19,87 * \%BTOS * Sulphides - 14,61 * \%QSRT * Pyrite + 137,75$	0,92
QSRT-GNS	Au Recovery - Linear	$Rec\ Au = -19,817x + 59,164$	0,93
	Cu Recovery - Linear	$Rec\ Cu = -9,22x + 78,78$	0,86
	Au mineralogical - Quadratic	$Rec\ Au = 13,19 * \%QSRT * Sulphides + 19,98 * \%GNS * Pyrite - 21,49$	0,99
	Mineralogical Cu - Quadratic	$Rec\ Cu = 8,61 * \%QSRT * Sulphides + 12,07 * \%GNS * Pyrite + 29,79$	0,93

In short, the results found are in line with expectations, given the results obtained in similar works that metallurgical recovery is a non-additive variable. Similar works were carried out, as in Käyhkö *et al*. (2020), however, the results were obtained through computer simulations, with the absence of practical supporting data. The proposition of mathematical models based on experimental results is also a differential in the study of geometallurgy with a focus on metallurgical recovery. It is worth mentioning that the proposed models need experimental confirmation.

CONCLUSION

The results obtained in this study indicate that the metallurgical recovery of copper and gold, an important parameter obtained in tests to estimate the metallurgical recovery of different lithologies, is a non-additive variable, due to the difference between experimental and theoretical values. Therefore, it is not possible to estimate the metallurgical recovery value through the weighted average of the recoveries obtained in the tests of pure samples. The impact of this work is on the recovery estimate gain in the beneficiation plant, since in the mine day-to-day, blends from different mining fronts are fed. Thus, this study constitutes a starting point for greater detailing of the metallurgical behavior in relation to the different blends, in addition to presenting the potential to provide greater predictability of the mass required to be fed to obtain a high recovery for different lithology blends of the ore.

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