

THE HOLLAND-BATT METHOD APPLIED TO A MAGNETIC WOLLASTONITE PURIFICATION

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ABSTRACT

Wollastonite is a Calcium mono-silicate mineral that has important properties to be applied in several branches of the industry such as plastics, ceramics, and electronics. The integral study of “La Juliana II” Skarn deposit (Córdoba, Argentina) includes an attempt to perform a dry magnetic Wollastonite separation and this work describes the use of the Holland-Batt method in its diagnosis. Holland-Batt built up a mathematical model for gravitational concentration methods in order to evaluate the mineral liberation performance at any stage of the beneficiation processes. The results indicate that the finer the heads are the purer in iron impurities the Wollastonite concentrates are. However, there is a paradox; since in spite of getting a Fe purer concentrate, other non magnetic minerals recoveries are also enhanced (Feldspars and Calcite). The applied model adapted to this case provides an excellent tool to analyse and give an explanation on the concentration problem. It has also shown the limitation of magnetic purification as a beneficiation process when a complex ore is treated. It is evident that process strategy and ore dressing methods ought to be assessed in order to achieve a useful Wollastonite concentrate.

KEY-WORDS: Magnetic separation, liberation degree, Wollastonite, Efficiency, Selectivity

1. INTRODUCTION

Wollastonite is a calcium mono-silicate mineral that has important applications in several industrial branches such as plastics, ceramics, and electronics. Nowadays, its commercial interest has improved. A skarn Wollastonite deposit "La Juliana II" has been found by Franchini in Córdoba (Argentina) and described elsewhere (Franchini et al. 1999; Cabanillas 1999; Balod 2002). The integral study of this deposit includes an attempt to perform an industrial dry magnetic purification. Previous separation tests were only successful in small samples utilising an Isodynamic Frantz Separator. Some years ago, Holland-Batt (1983) built up a mathematical model to evaluate, not only the performance of any stage of physical beneficiation but to calculate the liberation degree of a key component in minerals ores tested by gravitational techniques. In this work the application of the Holland Batt's liberation model is tried on the data collected from a series of dry magnetic separation tests carried out in a laboratory scale. This method has been explained elsewhere by his author (Holland-Batt, 1994) however, a brief outline is given here. This model assumes that the feed is composed by three kinds of particles: the locked particles that have got the same composition as that of the feed, free valuable particles and free gangue particles (Holland-Batt, 1993). Besides, it is claimed that at the start of the separation only free particles will be present, this yields to a proportion between free gangue and free valuable recoveries which must remain constant throughout the separation till the point of maximum Efficiency is reached. After this point any free valuable particle will not be present in the streams. The model may be also applied between two different species, considering one as the key or valuable component (Holland-Batt, 1994). The functions that allow to quantify this model are both the Efficiency (E) and the Selectivity (S) defined as

$$E_{ij} = R_i - R_j \quad (1)$$

$$S_{ij} = E_{ij}/R_i \quad (2)$$

E_{ij} : Cumulative efficiency function between i and j species or element.

S_{ij} : Cumulative selectivity function between i and j species or element.

R_i : Cumulative recovery function of i species.

In its development two important relationships are achieved

$$R_i^F = E_{ij}/S_{ij}^0 \quad (3)$$

$$G_{ij} = E_{ij}^{\max}/S_{ij}^0 = R_i^{\max} \quad (4)$$

Where the superscript F indicates the condition of free particle, S_{ij}^0 is the Selectivity at the start of the concentration process, when both R_i and R_j tend to zero; and G_{ij} is the liberation degree or liberation index.

One of the weakness of this model is the assumption that there are no free valuable or free key component recovery beyond the point of maximum Efficiency; this deficiency has been solved by performing free value-balances between the tailings which feed the next stage of concentration and the concentrate of this stage i.e.: rougher tails with scavenger concentrate; or cleaner tails-rougher concentrate (Holland-Batt, 1994; Correa, 2004).

The aim of this paper is to apply all these concepts to magnetic separation processes, particularly when lab-scale batch tests are performed. This is not a multiple exit stream operation but a process curve may be defined when the non-magnetic streams are retreated successively. So, the model will permit us to define an index of relative liberation that will help us to make a diagnosis on the studied sample. It makes sense to face up the problem from the point of view of the magnetic particles whose behaviour is responsible for the quality of the beneficiation. Instead of defining the beginning of the curve process as the maximum point of enrichment; it says, the point where the product will be

the purest in Wollastonite, it will be more convenient to choose the point of maximum magnetic species content as the starting point of the separation process, this way the Garnet-Diopside species (GD) will be the key component. In order to calculate the relative liberation degree between each of the main non-magnetic species and the bearing magnetic impurities: Garnet-Diopside (GD), it is necessary to determine E_{ij}^{\max} and S_{ij}^0 . To display the results the E_{GD} -species vs. S_{GD} -species graphs have been chosen. To quantify and qualify a physical separation it is always better to analyse it as a relationship between functions related to recoveries because the trends are shown clearer and sharper (Drzymala 2005 and 2007). To avoid graph calculations an empirical relationship, a formula, between the recoveries of the magnetic and the main non magnetic species (Wollastonite, Calcite, Feldspars) has been utilised. In this formula p_{ij} is a parameter to be obtained by fitting the recovery of the Garnet-Diopside (GD) vs. the recovery of each one of the other non magnetic species: Calcite, Feldspars and Wollastonite.

$$R_{GD} = \frac{\tanh[R_j/p_{GDj}]}{\tanh[1/p_{GDj}]} \quad (5)$$

$$S_{GDj}^0 = 1 - p_{GDj} \tanh[1/p_{GDj}] \quad (6)$$

$$E_{GDj}^{\max} = \frac{\sqrt{1 - p_{GDj} \tanh[1/p_{GDj}]}}{\tanh[1/p_{GDj}]} - p_{GDj} \operatorname{atanh} \left[\sqrt{1 - p_{GDj} \tanh[1/p_{GDj}]} \right] \quad (7)$$

2. EXPERIMENTAL

The skarn mineralogy is complex and it has variations in its composition in different geological outcrops. It was characterised by DRX, petrography and chemical analyses. The ore is composed by Wollastonite (W); (CaSiO_3), Vesuvianite ($\text{Ca}_2\text{Al}_2(\text{OH}, \text{F})\text{Si}_2\text{O}_7$, Garnet ($\text{Ca}_3\text{Al}_2(\text{SiO}_4)_3$) (G), Calcite (CaCO_3), a Na-K - Feldspars ($\text{K}[\text{AlSi}_3\text{O}_8]$, $\text{Na}[\text{AlSi}_3\text{O}_8]$), Diposide; ($\text{CaMgSi}_2\text{O}_6$) (D)), iron oxi-hydroxides (FeO_n) and quartz SiO_2 (Gómez et al. 2005). Garnet, Diopside and oxi-hydroxides are associated being this way the iron-impurity bearings. In this work, 16 kg of Wollastonite raw ore was ground till a minus-2 mm sample was produced. Then it was sized into four grain classes: (1020) $-2 + 0.85$ mm, (2040) $-0.85 + 0.425$ mm, (4070) $-0.425 + 0.212$ mm and (M70) minus 0.212 mm; the last one was discarded. These beneficiation processes were carried out in a laboratory Eriez magnetic separator equipment with a 7.5 cm diameter and 11 cm-height magnetic-cylinder built on the basis of rare earth oxides. The poles are set in alternated North-South slices, with a $0.2 \text{ T}^2\text{m}^{-1}$ specific magnetic force and 2 T is the maximum magnetic field. The sample was fed by a vibrating chute and finally on a belt. The applied frequency on the chute and the rotation speed may be set in order to control the mass rate feed; besides, a cutter is utilised as a divide for both magnetic and non-magnetic streams. The tests conditions are displayed in Table I.

Table I: Processing conditions of the magnetic purification tests*

Stage	Product	Speed of rotation [rad \times s $^{-1}$]	Mass rate/width [kg \times s $^{-1}$ \times m $^{-1}$]
1	Tailings	26.8	8.0
2	Middling 1	14.0	15.5
3	Middling 2	7.2	7.9
4	Middling 3 + Purified	4.2	20.3

*It was not necessary to produce a third middling in the 2040 fraction

The liberation degree was controlled on the test carried out on the 1020 fraction. Chemical analyses were performed on all the obtained products. The mineralogical composition was calculated on the basis of a rational analysis.

2.1. Results

The tailing of the 1020 fraction has a 40 % of locked grains; they have white and grey colours and the following minerals were identified: Wollastonite, Garnet, Feldspars, Vesuvianite, Diopside, Hiperstene, and small Quartz. In the Middling 2 about 30 % are still locked grains but mostly composed by Wollastonite and Vesuvianite. In the 1020 purified product almost all grains seem to be completely liberated.

The grinding and sizing produce a chemical zonation that is shown in Table II and the results of the magnetic separation are shown in Tables III, IV and V.

Table II: Grinding and sizing process. Chemical Analysis

Product	Size [mm]	Yield [%]	Analysis [%]							
			CaO	SiO ₂	Fe ₂ O ₃	MgO	Al ₂ O ₃	Na ₂ O	K ₂ O	L.O.I.
1020	-2.000 +0.850	49.1	29.94	52.52	3.28	1.57	8.00	1.57	1.01	1.13
2040	-0.850 +0.425	14.4	28.21	53.09	3.57	1.71	8.75	1.80	1.14	1.09
4070	-0.425 +0.212	9.2	26.90	52.32	3.71	1.75	9.35	1.89	1.41	1.40
M70	-0.212	27.3	32.04	50.80	3.31	1.24	6.61	1.24	1.08	1.63
Composite		100.0	29.93	52.02	3.36	1.51	7.84	1.54	1.08	1.28

Table III: 1020 fraction. Magnetic separation test

	Yield [%]	Composition [%]				Distribution [%]			
		W	Calcite	Feldspars	GD	W	Calcite	Feldspars	GD
Tails	20.1	43.4	2.4	20.5	24.1	16.5	21.3	22.1	27.7
Middling 1	44.7	40.9	2.9	23.9	21.8	34.5	52.4	57.1	55.8
Middling 2	12.7	57.8	2.0	19.3	13.3	13.9	11.1	13.2	9.7
Middling 3	2.5	67.3	3.2	13.3	10.2	3.2	3.5	1.7	1.5
Purified	20.0	84.5	1.3	5.5	4.7	31.9	11.7	5.9	5.3
Composite	100.0	52.9	2.3	18.7	17.4	100.0	100.0	100.0	100.0
Head 1020		49.8	2.6	19.3	18.6	-	-	-	-

Table IV: 2040 fraction. Magnetic separation test

	Yield [%]	Composition [%]				Distribution [%]			
		W	Calcite	Feldspars	GD	W	Calcite	Feldspars	GD
Tails	37.8	35.9	1.5	18.8	33.0	28.6	25.7	32.1	67.0
Middling 1	35.5	45.6	2.3	25.9	15.1	34.1	38.1	41.5	28.8
Middling 2	4.6	55.0	3.6	27.1	6.4	5.3	7.8	5.6	1.5
Purified	22.1	68.5	2.7	20.8	2.2	32.0	28.4	20.8	2.7
Composite	100.0	47.4	2.1	22.2	18.6	100.0	100.0	100.0	100.0
Head 2040	-	45.4	2.5	22.0	20.3	-	-	-	-

3. DISCUSSION

The results are obvious at first glance: the finer the feed are the less are the iron bearing species in the Wollastonite purified product. However, there is a paradox: in spite of getting a purer Wollastonite product in iron, the recoveries of Feldspars and Calcite are enhanced. On applying the Holland-Butt's model a kind of diagnosis will be facilitated. In Table VI the model parameters of the separation processing are displayed, the performance curves of processing are shown in Figures 1, 2 and 3.

The Figure 4 shows how all the liberation indices G vary with the average fraction size. The performed calculations gave an obvious trend: when the average size of the feed becomes finer, the relative liberation index G increases in

Table V: 4070 fraction. Magnetic separation test

	Yield [%]	Composition [%]				Distribution [%]			
		W	Calcite	Feldspars	GD	W	Calcite	Feldspars	GD
Tails	43.8	35.7	1.9	13.1	38.9	36.1	31.0	23.7	85.8
Middling 1	17.7	44.5	3.5	28.0	11.8	18.0	23.3	20.3	10.5
Middling 2	7.6	50.9	2.9	33.3	3.7	9.0	8.4	10.5	1.5
Midlings 3	1.7	53.4	2.9	32.8	2.2	2.0	1.8	2.2	0.1
Purified	29.2	51.7	3.2	36.0	1.4	34.9	35.5	43.3	2.1
Composite	100.0	43.4	2.7	24.3	19.9	100.0	100.0	100.0	100.0
Head 4070	-	41.6	3.2	24.3	20.9	-	-	-	-

each of the main non-magnetic species. Now, the paradox has been clarified in a simple way by the model and in agreement with Figure 4. While the Wollastonite liberation index G was the largest, a 85 % Wollastonite purified product was collected (1020 fraction). On the contrary, when the liberation indices of Calcite and Feldspars are at the same level as the Wollastonite's (2040 and 4070 fractions) the Wollastonite contents fall dramatically in the purified products of these size fractions; 69 and 52 %; in spite of keeping on almost the same Wollastonite recoveries in all the purified products: 32 to 35 %. It is evident that when the liberation conditions of Feldspars and Calcite improve they both compete strongly against Wollastonite on being collected into the purified products.

4. CONCLUSION

The results showed that at the same time that the magnetic impurities drop the non magnetic Feldspars and Calcite increase in the Wollastonite purified products of the finest fractions 2040 and 4070. This behaviour is well explained using the parameters that the model of Holland-Batt provides. The applied model adapted to these circumstances is an excellent and necessary tool to analyse and give a diagnosis on these sorts of processes. A plain explanation has been produced from the point of view of a liberation analysis and it has shown the limitation of the magnetic purification as a beneficiation process when a complex ore is treated. It is evident, in this case, that strategies and ore dressing methods

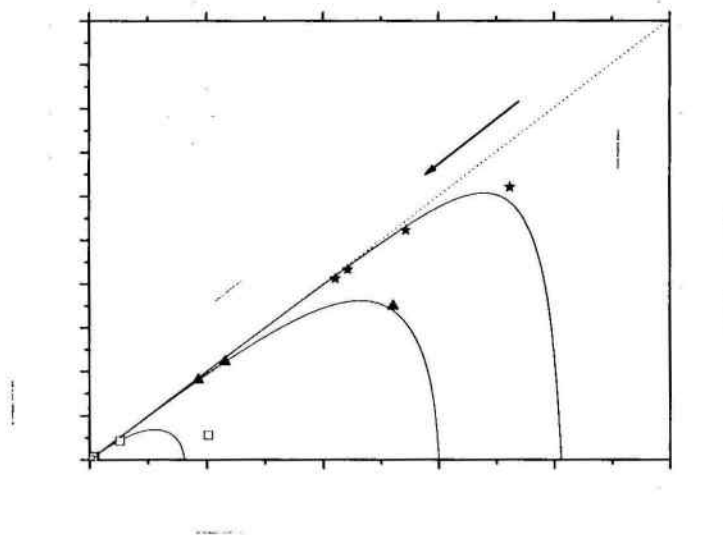


Figure 1: Efficiency vs. Selectivity in different fraction sizes. GD-Feldspars

ought to be assessed in order to achieve the goal: a best grade of a Wollastonite purified product. It is concluded that it is possible to evaluate the relative liberation degree of the main non-magnetic species applying the same concepts as Holland-Batt developed for gravimetric concentrations. The proposed future circuits of treatments should be analysed in the light of the liberation degree characteristics of the main species. Finally, the model seems to be improved by an Efficiency vs. Selectivity graph and a parameter (ρ) whose value is directly related to the locked particles content.

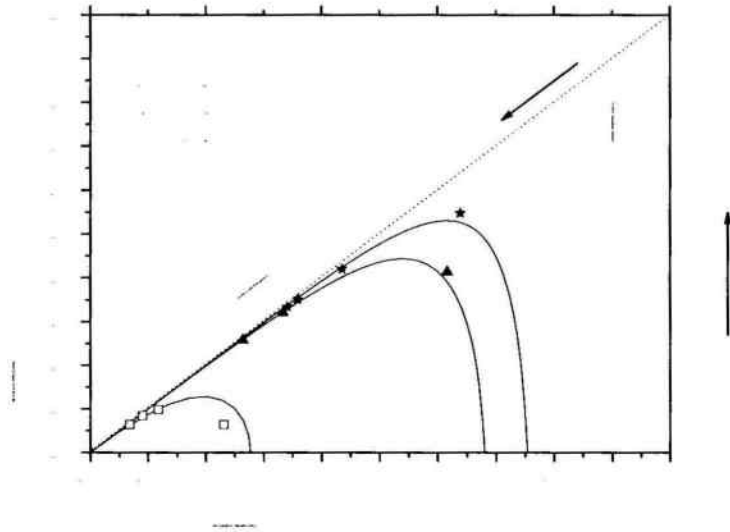


Figure 2: Efficiency vs. Selectivity in different fraction sizes. GD-Calcite

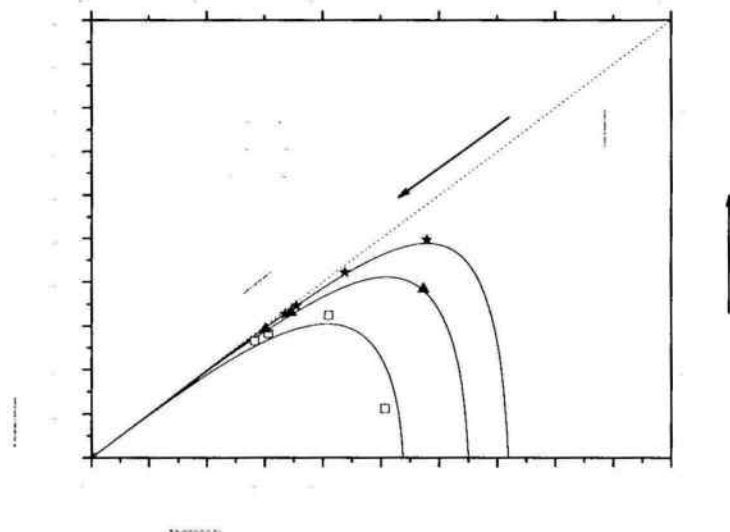


Figure 3: Efficiency vs. Selectivity in different sizes. GD-Wollastonite

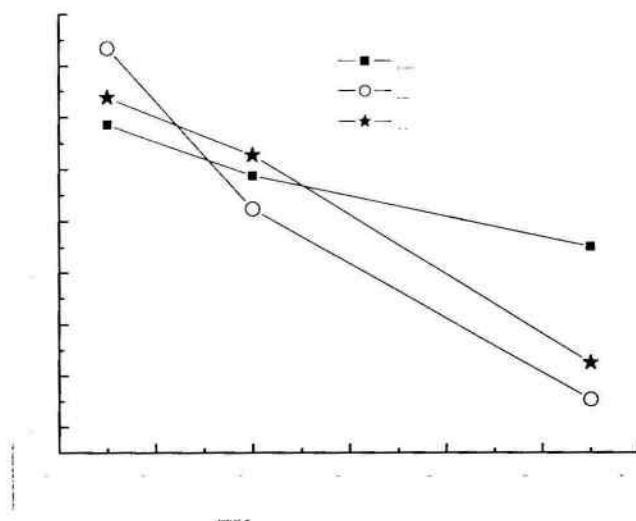


Figure 4: Liberation Indices vs. Average size

Table VI: Characteristic parameters of the separation processing

Fraction	Parameters	Calcite	Feldspars	Wollastonite
1020 Average size 1300 μm	p	0.898	1.292	0.476
	E^{max} [%]	12.8	6.9	31.1
	S^0	0.277	0.162	0.538
	G [%]	46.3	42.7	57.6
2040 Average size 600 μm	p	0.321	0.405	0.352
	E^{max} [%]	45.2	36.8	41.9
	S^0	0.680	0.600	0.650
	G [%]	66.4	61.2	64.4
4070 Average size 300 μm	p	0.246	0.188	0.281
	E^{max} [%]	54.2	62.3	49.8
	S^0	0.754	0.812	0.719
	G [%]	71.9	76.7	69.3

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