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Chemistry

Size effects in itabirite jigging under high frequency

Efeitos granulométricos na jigagem de itabiritos sob alta frequência

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ABSTRACT

Concentration jigs have been used in ore dressing since the Middle Ages. Contrary to other sorting methods, gravity separation is a unit operation that implies low operational and environmental costs. This work describes the effect of particle size on separation efficiency using synthetic quartz and hematite mixes, simulating itabirite ores. The technological parameters of a Harz-Denver type jig were studied as a rougher stage at bench scale, employing previously sized samples. The experiments were carried out using 12 size classes, under a stroke amplitude of 7.0 mm and various pulse frequencies, including values above those historically practiced in the industry. Hematite content in prepared feeds was 40 %, 50 % and 60 %. It was observed that the jig has better performance with feed contents below 50 % hematite in the case of blends of middle and fine particles. The results were very promising. The concentrate average hematite grade was 89.35 %, from 40 % hematite feed, while the corresponding recovery was 97.62 % and a very high Gaudin's selectivity index of 12.37. Nevertheless, the jig did not perform so well when it treated global samples (mix of all size classes), indicating the importance of the proper granulometric grading of the ore particles.

Keywords: Gravity concentration; Mineral jig; Iron ore; Itabirite

RESUMO

Os jigues têm sido usados no beneficiamento de minério desde a Idade Média. Ao contrário de outros métodos de concentração, a separação densitária implica baixos custos operacionais e ambientais. Este trabalho descreve o efeito do tamanho das partículas na eficiência de separação utilizando misturas sintéticas de quartzo e hematita, simulando minérios itabiríticos. Os parâmetros tecnológicos de um jigue tipo Harz-Denver foram estudados no estágio de desbaste em escala de bancada, empregando amostras minerais previamente bitoladas. Os experimentos foram efetuados a partir de 12 classes granulométricas, com amplitude de curso de 7,0 mm e diversas frequências de pulsação, incluindo valores acima dos historicamente praticados na indústria. O teor de hematita nas alimentações preparadas foi de 40 %, 50 % e 60 %. Observou-se que o jigue tem melhor desempenho usando alimentação abaixo de

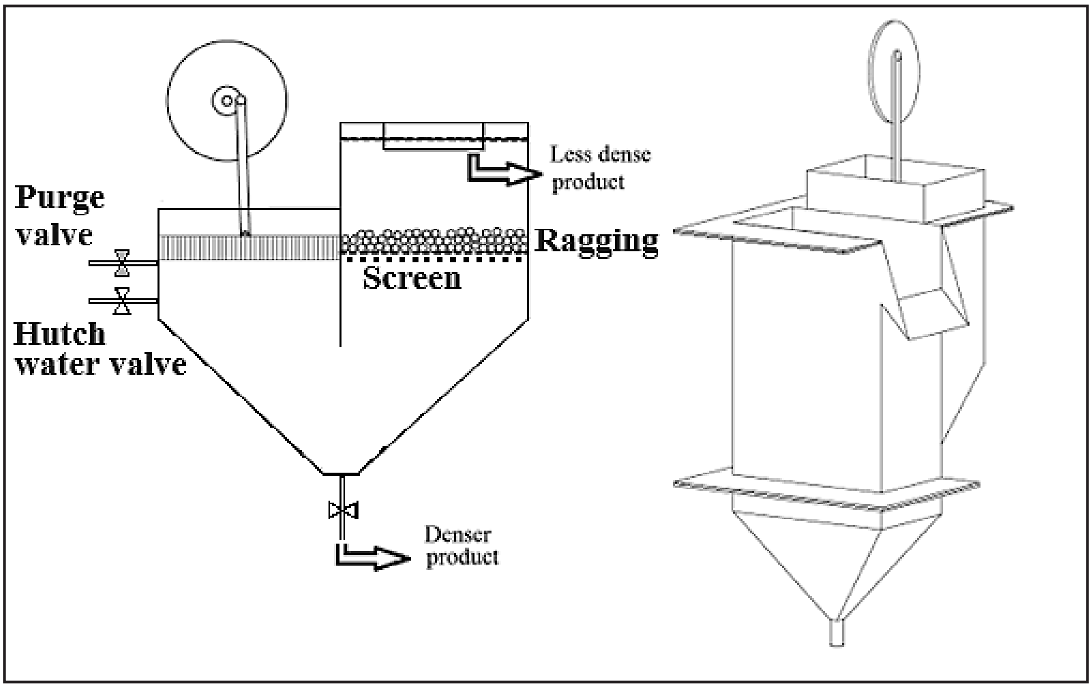
50 % de hematita, no caso de mesclas de partículas médias e mesclas de partículas finas. Os resultados foram muito promissores. O teor médio do concentrado foi de 89,35 % de hematita, a partir de alimentação com 40 % de hematita, ao passo que a recuperação correspondente foi de 97,62 % e índice de seletividade de Gaudin muito elevado de 12,37. Porém, o jigue não teve um desempenho tão bom quando tratou amostras globais (mescla com todas as classes de tamanho), indicando a importância do bitolamento granulométrico adequado do minério.

Palavras-chave: Concentração densitária; Jigue; Minério de ferro; Itabirito

1 INTRODUCTION

Jig is gravity concentration equipment that is used since long time ago because of its efficiency, simplicity of operation, and maintenance (Figure 1).

Figure 1 – Schematic drawings of a Harz-Denver mineral jig



Source: Authors (2025)

In addition to jigging and other density-based processes, the more recent froth flotation technique has been mostly used in the processing of complex ores, in particular in case of ores with a high content of fines, for which gravity processes are generally ineffective (in virtue of drag forces). However, even in these cases, at least a portion of the ore is amenable to treatment by gravity concentration. Assisting flotation machines, jigs and helical concentrators (inappropriately called *spirals*) are widely used in iron ore processing. In this context, the present work aimed at quantifying the effect of ore particle sizes and pulse frequency on the efficiency of iron ore concentration by jigging.

Separation of minerals by their specific gravity difference is the result of three basic mechanisms in jigging: hindered settling, differential initial acceleration, and interstitial trickling. These driving forces lead to a concentration gradient in the separation bed (Gaudin, 1939; Kelly & Spottiswood, 1982; Wills & Napier-Munn, 2005; Ya-Li et al., 2008). The effect of stroke amplitude and frequency on the progress of bed stratification during jigging is well established (Gaudin, 1939. Taggart, 1954. Mukherjee et al., 2005. Jinnouchi et al., 1984; Mukherjee et al., 2006).

Within the range of amplitude and frequency studied by Silva et al. (2016), in a Harz-Denver jig, particle size has proven to be a more important factor than pulse frequency. According to Mukherjee and Mishra (2006), pulsation frequencies too high or too low cannot provide sufficient time and particle mobility for separation.

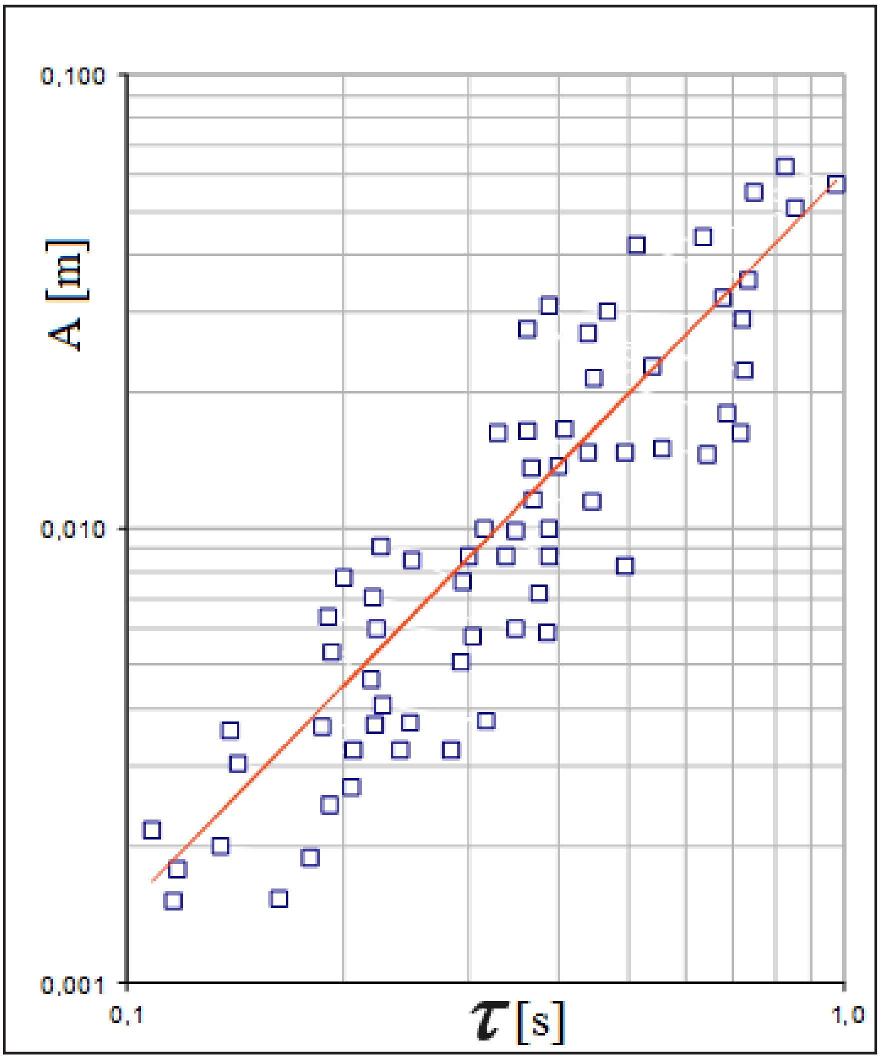
Luz (2023), from industrial data available in the literature (Kizevalter, 1960 apud: Steiner, 1996) as plotted in Figure 2, could estimate the expected stroke amplitude as a function of the jig's pulsation period *(τ)* by Equation (1).

$$A = 0.06075 \times \tau^{1.618} = 0.06075 \times f_p^{-1.618} \tag{1}$$

In which: A — stroke amplitude at pulsation chamber [m]; τ — cycle period of jig [s]; f_p — pulsation frequency [Hz].

From the energetic point of view, Mayer (1964) established a formalism where jigging efficiency is associated with the evolution of the gravitational potential energy of the system (pulsating pulp), that is, the lowering of its center of gravity (Mayer, 1964; Sampaio & Tavares, 2005). There has been criticism to the first order differential equation resulting from this approach, for disregarding complex effects of particle mechanics (Aguiar, 2015), such as the Brazilian nut effect (Brito & Soto, 2010; Li et al, 2023) and the related phenomenon called the whale effect (Gallas et al, 1996).

Figure 2 – Correlation between parameters for cycle period *(τ)* and stroke amplitude (A) for several industrial jigs (Data after Kizevalter)



Source: Authors (2025)

2 MATERIALS AND METHODS

Artificial mixtures of hematite and quartz were used to carry out all concentration experiments. Sinter feed concentrate from a banded iron formation at Pedreira Um/Valemix mine, in Catas Altas municipality (inside the so-called Brazilian Iron

Quadrangle), was used as hematite sample. This material was comminuted by jaw crusher, roller crusher and ball mill until enough material had been obtained. Then the ground material was sized between 0.053 mm and 3.350 mm (the fraction below 0.053 mm was discarded). On the other hand, the compact quartz sample, coming from Ouro Preto municipality, after hand-hammered, was also further submitted to the same comminution and sizing procedure mentioned above.

The openings of the thirteen sieves used were: 3.35 mm, 2.38 mm, 1.68 mm, 1.19 mm, 0.84 mm, 0.59 mm, 0.42 mm, 0.297 mm, 0.21 mm, 0.149 mm, 0.105 mm, 0.074 mm and 0.053 mm.

In the initial experimental campaign, tests were made using aliquots made up of each of size classes (the 12 classes bellow 3.35 mm) separately. Subsequently, blended samples were prepared according to three sized ranges (categorized by their theoretical terminal velocity) for the second campaign. In this line, the class partitioning criterion adopted was terminal velocity : for hematite (here with specific mass of 4860 kg/m^3, and Wadell's mean sphericity close to 0.75) under a mass concentration of 35.0 % (9.97 % by volume). The following size-graded ranges were obtained for both hematite and quartz:

Coarse fraction: between 0.595 mm and 3.350 mm, with hematite terminal velocities between 0.0623 m/s and 0.1551 m/s;

Middle fraction: between 0.297 mm and 0.595 mm, with terminal hematite velocities between 0.0274 m/s and 0.0623 m/s;

Fine fraction: between 0.053 mm and 0.297 mm, with hematite terminal velocities between 0.0015 m/s and 0.0274 m/s.

In order to calculate the above-mentioned sized ranges, the drag coefficient (C_d) corresponding to asymptotical Reynolds number (*Re*) of particles was determined by the equation from Turton and Levenspiel (1986):

$$C_d = \frac{24}{Re} \times (1 + 0.173 \times Re^{0.657}) + \frac{0.413}{1 + 16300 \times Re^{-1.09}} \quad (2)$$

In turn, the hindrance effect caused by volume concentration of solids (c_v, considered in this instance as 9.97 %) was calculated using the equation from Luz (2009), expressed by Equation (3), in terms of terminal settling velocity (v_t).

$$v_t = v_{t0} \times f(c_v) = v_{t0} \times (1 - c_v^{0.919})^{4.861} \quad (3)$$

Where v_{t0} is the terminal velocity of an isolated particle (c_v = 0). The preceding equation yields results that are highly similar to those obtained by applying the Steinour equation (Steinour, 1943; Dallavalle et al., 1958).

After sample preparation, experiments were performed on a Harz-Denver concentration jig, varying the ragging thickness and stroke frequency. All experiments were duplicated.

A laboratory jig with an electric motor at 28.92 Hz (1735 rpm) and a CFW 500 frequency inverter to vary the pulse frequency was used. The jigging chamber had an effective area of 0.00175 m^2. The pulsing mechanism was a rubber diaphragm driven by a crank eccentrically coupled to a rotating shaft through a bearing.

Jigging tests were performed with 1.000 kg samples. Taggart's concentration criterion for the system under study is 2.34, indicating relatively easy separation for similarly shaped particles. However, morphological analysis by optical microscopy showed that the hematite particles had lower sphericity than the quartz particles, implying a lower effective value of the concentration criterion after Burt's correction (Sampaio & Tavares, 2005).

Concentrate grade (proportion of hematite), metallurgical recovery, and Gaudin's selectivity index (*S.I.*) were the technological parameters used to evaluate the experimental results, with the selectivity index being the main parameter of comparison.

The hematite content of the samples was calculated via water pycnometry (with at least duplicate tests), since the samples were made up of previously known free particles (that is, particles that were not interconnected), since they were the result of synthetic mixtures. Therefore, the hematite content (x_h) was calculated using the following equation:

$$x_h = \frac{\rho_h \times (\rho - \rho_g)}{\rho_s \times (\rho_h - \rho_q)} \tag{4}$$

Where: ρ_s, ρ_h, and ρ_q are sample density, hematite density, and quartz density, respectively (in coherent physical units).

In turn, the recovery was corrected by subtracting the mass of hematite contained in the remnant material (leftover) on the jig screen after the test from the mass of hematite fed, resulting unbiased value. The expression for this corrected metallurgical recovery (R^*_{met}) is (uppercase letters stand for masses, while lowercase letters stand for contents):

$$R^*_{met} = \frac{c \times C}{f \times F - r \times R} = \frac{c \times C}{f \times F - r \times (F - C - T)} \tag{5}$$

The parameters of the preceding and following equations are: *F* — mass of solids in feed [kg]; *C* — mass of solids in concentrate [kg]; *R* — mass of residual solids on jig screen [kg]; *T* — mass of solids in tailings [kg]; *f* — hematite grade in feed [–]; *c* — hematite grade in concentrate [–]; *r* —hematite grade in residual on jig screen [–]; *t* —hematite grade in tail [–]. In reality, this correction for leftover material is only important for small samples (as is the case here). Indeed, for any feed mass greater than the minimum feasible for the equipment, the residual amount of solid on the jig screen will remain the same. As a matter of fact, when the feed mass tends to infinity (while keeping the feed grade), the correction tends to zero, reducing the previous expression to its canonical form.

Regarding Gaudin's selectivity index, its expression is:

$$S.I. = \sqrt{\frac{c}{t} \times \left(\frac{1-t}{1-c}\right)} \quad (6)$$

It is noteworthy the expression for the selectivity index was kept intact (without correction for leftover material on screen) out of respect for tradition. This approach strengthens the conclusions, as it is actually a conservative estimate (for small-scale experiments).

Interestingly, preliminary tests showed that frequencies significantly higher than those usually employed in the mineral industry gave good results for this particulate material. Optimum frequencies (resulting in higher *S.I.* values) were determined for each of the twelve isolated size classes studied.

When processing size-graded samples, a stroke frequency of 5.54 Hz (332.7 rpm) was used for the coarse fraction (between 0.595 mm and 3.350 mm), a frequency of 7.17 Hz (430.4 rpm) was used for the middle fraction (0.297 – 0.595 mm), and 8.9 Hz (533.5 rpm) was used for the fine fraction (0.053 – 0.297 mm). Two layers of steel balls as ragging were employed. Steel balls of 4 mm in diameter were used for particulate material below 0.595 mm and steel balls of 6 mm for coarser synthetic ore. The average operating time was set at 166 seconds for the jigging process. All concentration experiments were performed with invariant stroke amplitude of 7.0 mm. Prior to the start of each experiment, any air previously present in the pulse chamber was removed via the purge valve, so as not to interfere with the oscillatory dynamics of the flow (given the discrepancy between the compressibility parameters of air and water).

For tests with the isolated size classes, the inlet mass flow rate of hutch water was adopted as been 38.22 % of the terminal velocity of hematite particles of each class, resulting in values from 1.4 x 10^{-6} m^3/s (for class with mean diameter of 0.063 mm) to 112.8 x 10^{-6} m^3/s (mean diameter of 2,865 mm). The same criterion was followed for the size-graded material, taking the range average diameter to calculate the terminal velocity. Thus, hutch water flow rate has resulted equal to 89.4 x 10^{-6} m^3/s for the coarse fraction (0.595 mm – 3.350 mm), 29.3 x 10^{-6} m^3/s for middle fraction (0.297 – 0.595 mm), and 6.51 x $10^{-}6$ m^3/s for fine fraction (0.053 – 0.297 mm).

The final stage of the experimental campaign of gravity concentration was done using the so-called global samples. Global sample (specific for a given feed grade) was prepared by adding up each of the 12 size classes appropriately (previously individualized by sieving). In order to emphasize size effects, blending of all 12 size classes was done in the same proportions, resulting the target feed grade. For example, to prepare 1,000 kg of a global sample with 40 % hematite, parcels of 0.03333 kg of hematite were mixed with parcels of 0.05000 kg of quartz from each of the twelve size classes, up to reach 1.000 kilogram: 12 x (0.03333 + 0.05000) = 1.0000 kg. In this final stage, the effect of the feed grade and pulsation frequency on the metallurgical performance of the jigging process was studied.

3 RESULTS

3.1 Experiments using isolated size classes

The mean specific solid flow rate was kept constant for all tests and resulted equal to 3.44 kg of solids per second per square meter of jig screen, which is equivalent to 12.4 t/(h.m^2). The metallurgical performance of the experiments by size class, under their respective optimal frequencies, is summarized in Table 1.

High selectivity and high concentrate contents were obtained by using exceptionally high frequencies (compared to industrial practice). It was possible to obtain concentrate grade equal to 95.94 % hematite and very high selectivity index of 16.11 for material between 0.595 mm and 0.42 mm (under frequency of 7.16 Hz), as seen in Table 1. The concentrate grade for material between 0.053 mm and 0.074 mm, was 86.03 % hematite, with selectivity index of 6.90 (under frequency of 9.23 Hz).

Table 1 – Metallurgical accounting of experiments for size class under optimal frequencies and using samples with 40 % hematite in feed

Class	x [mm] (*)	f_p [Hz] (*)	hematite grade [%]			Technical indices		
			Feed	Concentrate	tail	Yield [%]	Recovery [%]	S. I. [–]
1	2.38	5.22	41.04	59.59	22.55	57.04	77.82	2.60
2	1.68	5.35	39.35	94.14	23.81	13.92	39.00	5.41
3	1.19	5.36	41.10	91.83	22.72	27.28	60.26	6.29
4	0.84	5.41	37.62	93.38	19.76	24.95	61.10	7.71
5	0.59	7.15	40.15	93.24	25.41	18.39	45.26	5.73
6	0.42	7.16	35.04	95.94	7.56	28.85	83.73	16.11
7	0.297	7.18	41.52	92.03	23.26	28.65	61.37	6.50
8	0.21	8.58	43.21	54.41	35.54	38.52	48.96	1.41
9	0.149	8.77	37.76	54.33	22.61	52.86	72.93	2.24
10	0.105	8.88	38.39	49.52	37.36	32.32	38.76	2.91
11	0.074	8.99	40.69	64.05	26.82	34.52	55.74	2.08
12	0.053	9.23	37.09	86.03	12.35	35.53	79.34	6.90

Source: Authors (2025)

(*) x = inferior screen aperture of the class; f_p = piston (plunger) frequency

3.2 Experiments using size-graded feeds (coarse, middle and fine fractions)

Jigging test using size-graded samples (coarse fraction, middle fraction and fine fraction) were carried out employing "optimal" frequencies for the respective sized sample. The "optimum" frequency (in the jig chamber, i.e., in the piston), for a given sized range, would the mass-weighted average of the optimum frequencies for each of the particle size classes constituting the said double-bounded fraction (upper and lower limits in size), unless small operational adjustments, when actually carrying out the experiments. Table 2 shows the results of this procedure.

Table 3 shows that, in all frequencies tested, the best results were obtained in the middle and fine ranges.

Figure 3 shows that the tests with 40 % hematite in the feed were very selective, resulting in a mean concentrate grade of 97.62 %, with a selectivity index of 12.37. While for the fine range, 61.64 % of hematite was obtained in the concentrate, with a selectivity index of 2.62.

For testing with the middle range with a content of 50 % hematite in feed stream, the concentrate grade was 94.57 % and the selectivity index was 7.01, while for the fine range, the concentrate grade resulted 64.08 % hematite and the corresponding selectivity index was equal to 2.00.

Table 2 – Composition of size class and operating frequency for size-graded samples

Size Class	**Sieve opening [mm]**	**Mass fraction in sized sample**			**Optimal frequency for class [Hz]**
		Fine range	**Middle range**	**Coarse range**	
1	0.053	20.0 %	0.0 %	0.0 %	9.23
2	0.074	20.0 %	0.0 %	0.0 %	8.99
3	0.105	20.0 %	0.0 %	0.0 %	8.88
4	0.149	20.0 %	0.0 %	0.0 %	8.77
5	0.21	20.0 %	0.0 %	0.00 %	8.58
6	0.297	0.0 %	50.0 %	0.0 %	7.18
7	0.42	0.0 %	50.0 %	0.0 %	7.16
1	0.053	0.0 %	0.0 %	20.0 %	7.15
2	0.074	0.0 %	0.0 %	20.0 %	5.41
3	0.105	0.0 %	0.0 %	20.0 %	5.36
4	0.149	0.0 %	0.0 %	20.0 %	5.35
5	0.21	0.0 %	0.0%	20.0 %	5.22
Operating frequency for graded fraction [Hz]		8.9	7.17	5.54	–

Source: Authors (2025)

Table 3 – Concentrate grade for coarse, middle and fine fractions (parcels) and S. I.

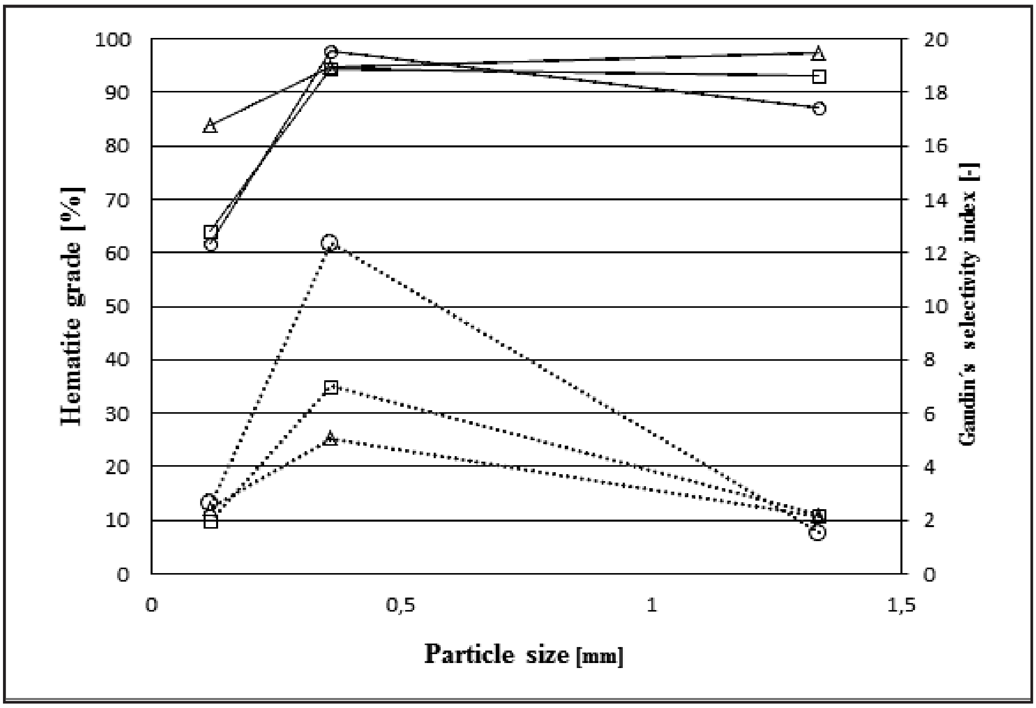
Hematite in feed [%] →	***40 %***	***50 %***	***60 %***	***40 %***	***50 %***	***60 %***
Fraction's average diameter [mm] ↓	**Hematite in concentrate [%]** ↓			**Gaudin's selectivity index [-]** ▯		
1.340 (coarse)	87.08	93.27	97.40	1.54	2.20	2.17
0.358 (middle)	97.62	94.57	94.89	12.37	7.01	5.06
0.1182 (fine)	61.64	64.07	83.94	2.62	2.00	2.45

Source: Authors (2025)

The solid lines of Figure 3 show the concentrate content (for feed grade of 40 % hematite), while the dotted lines represent the corresponding Gaudin's selectivity index. One can see in the feed grades below 50 % hematite that the jig has proved more efficient (including the case of tests with hematite feed content below 30 %, not reported here for the sake of brevity).

Statistical variability of the experiments, considering all feed contents (40 %, 50 % and 60 %), was characterized by their coefficient of variation of the selectivity index between the duplicates. Thus, a coefficient of variation of 3.65 % was obtained for the coarse range, 1.10 % for the middle range and 0.51 % for the fine range. These figures show experiments with very low variability.

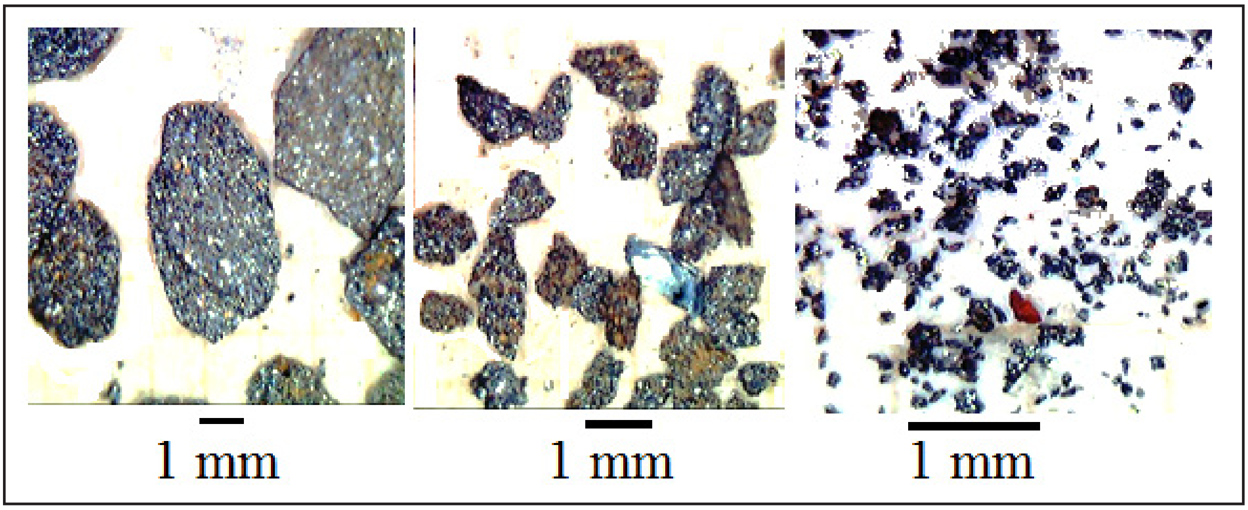
Figure 3 – Concentrate grade (solid lines) and selectivity index (dotted lines) *versus* mean diameter of sized fractions



Source: Authors (2025). Circles: 40 % hematite in feed; squares: 50 % hematite in feed; triangles: 60 % hematite in feed

Mainly for illustrative purposes, the Figure 4 shows the visual features of typical concentrates resulting from the jigging of size-graded feeds. On the left, one can see a concentrate from coarse range sample; at the center a concentrate from middle range sample and on the right, it can be seen a concentrate from fine range sample. In all cases, rich contents can be observed, concerning a rougher stage.

Figure 4 – Concentrate for coarse range (left), middle range (center) and fine range (right)



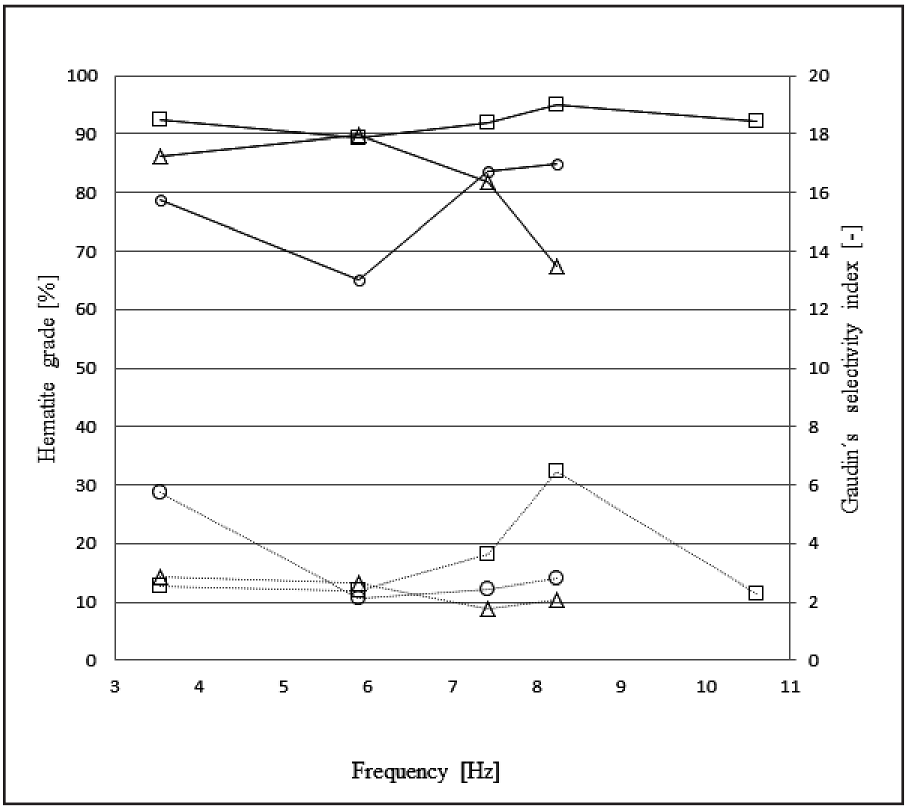
Source: Authors (2025). Scale bars represent 1 mm

3.3 Experiments using global samples

Similarly, Figure 5 illustrates test results employing global samples for 40 %, 50 %, and 60 % hematite head contents, respectively. For this stage of the work the pulsation frequencies of 3.5 Hz, 5.9 Hz, 8.2 Hz and 10.6 Hz were tested. It was verified the best selectivity index under the frequencies of 3.5 Hz for feed of 40 % hematite, with a concentrate grade of 78.84 % and a selectivity index of 5.77, as shown in Table 4, demonstrating highly promising results.

In the same direction as these experimental numbers, statistical test variability using global samples (blending of all 12 size classes in equal proportions) was also appropriately low. With 40 % hematite in the feed, the experiments had standard deviation of the selectivity index of 0.019, while its coefficient of variation was 1.87 %.

Figure 5 – Concentrate grade (solid lines) and selectivity index (dotted lines) *versus* mean diameter of global samples



Source: Authors (2025). Circles: 40 % hematite in feed; squares: 50 % hematite in feed; triangles: 60 % hematite in feed

Table 4 – Process performance using global samples *versus* frequency

Hematite in feed [%] → **Frequency [Hz]** ↓	***40 %***	***50 %***	***60 %***	***40 %***	***50 %***	***60 %***
	Hematite in concentrate [%] ↓			**Gaudin's selectivity index [-]** ↓		
3.53	78.84	92.40	86.22	5.77	2.57	2.85
5.89	65.08	89.22	89.85	2.15	2.42	2.65
7.42	83.77	91.82	81.94	2.45	3.64	1.79
8.24	84.90	94.88	67.40	2.81	6.45	2.09
10.60	–	92.08	–	–	2.28	–

Source: Organized by the authors (2023)

Similarly, tests with 50 % hematite in feed resulted standard deviation of the selectivity index equal of 0.019 and its coefficient of variation of 1.95 %. For the tests with 60 % of hematite in the feed, the corresponding standard deviation was 0.017, while its coefficient of variation was 1.77 %.

4 CONCLUSIONS

The three best results of the jig tests using the isolated size classes were obtained with the classes between 0.42 mm and 0.59 mm, between 0.84 mm and 1.19 mm, and finally the class between 0.053 mm and 0.074 mm. In all cases, the experiments were performed at frequencies above those usually practiced in industry.

For the jig tests employing size-graded fractions the best results were observed with the middle range samples (with average particle diameter of 0.36 mm), resulting in high Gaudin's selectivity indices for all the content levels studied. The authors observed that the jig performs better at low feed grades (40 % hematite and bellow) using middle and fine range samples, at least with the stroke amplitude and under pulse frequencies tested within this work.

For the tested material, it can be concluded that the jig concentrates better particles between 0.42 mm and 0.297 mm, at least in the frequency range studied (substantially higher than those commonly practiced in the industry) and stroke (plunger amplitude) equal to 7.0 mm.

Apart from occasional discrepancies arising from morphometric effects, the conclusions drawn in this work can be extrapolated to other mineral assemblages (provided that they exhibit a high degree of liberation of the constituent particles of the ore).

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