Tecnological tests of the pegmatites waste at Alto Dois Irmãos/PB in the Borborema Pegmatitic Province/BPP

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Abstract

In the county of Pedra Lavrada – PB, various mineral occurrences of pegmatite are observed with prominence at Alto Dois Irmãos – PB, where quartz, feldspar and mica are mined. The understanding of mineral constituents is fundamental to define their industrial employment and to implement improvements in the beneficiation process. The proposal of this research is the detailed characterization and proof of that part of the ore (quartz) considered waste, presenting low poisoning (Fe_2O_3) and high silica (SiO_2) content, to enable its industrial use. Besides that, to minimize the environmental impact through the reuse of this waste, and to determine the correct utilization of the milling equipment. For the pegmatite characterization, done were density determination tests, mineralogical identification by X-ray diffraction (XRD), chemical analysis by fluorescents X-rays and morphological analysis by scanning electron microscopy (SEM/EDS). Then tests were done for the *Work Index* (WI) calculous and consequently the empirical determination of the dimensions (LxD) of the pebble mill. The sterile presented a medium density of 2.66g/cm³, majority chemical composition of silicon and oxygen and quartz as the main mineralogical stage, indicating that this material has high purity. The. The *Work Index* (WI) was 15.9 kwh/t showing that this material can be considered resistant to breaking in the grinding process. The necessary energy to the milling was defined in 11.52 kwh/st, that corresponds to 57.28 HP. This power allowed the mill selection with diammeter and length of 1.83m, that provides the production maximization and the energy saving.

keywords: characterization; sterile; pegmatite; quartz; residue.

1. Introduction

Pegmatite extraction activities occur in arid regions, such as the Central Potiguar Mesoregion and the Seridó Oriental Paraibano Microregion, both located in the Borborema Pegmatitic Province – BPP (Luz *et al*., 2003). The BPP mineralized pegmatites (metalic minerals, industrial minerals, mineral-gem) are located in parts of Paraiba and Rio Grande do Norte states and are concentrated preferably in the counties of Parelhas, Equador, Carnaúba dos Dantas, Picuí, Pedra Lavrada, Nova Palmeira, Frei Martinho, Juazeirinho and Junco do Seridó (Idema, 2010). These pegmatites are constituted by potassium feldspar, quartz, muscovite and in less quantity: albite, biotite, black tourmaline and garnet (Castro & Jatobá, 2006). The mineralization can occur with Ta-Nb, Be, Li, mica and kaolin (Luz *et al*., 2003). The Borborema Pegmatitic Province is considered to be the second largest Brazilian pegmatitic province (Castro & Jatobá, 2006) because it contains a significant quantity of mineralized mineral bodies and varieties of rare minerals.

Generally, these pegmatites are explored by prospectors and mid- or small-sized ore beneficiation companies. The pegmatite beneficiation occurs in comminution circuits, where the primary and secondary crushing are done in jaw crushers. The product from crushing goes to a two-deck inclined sieve and the withheld material goes to a pebble mill, where the material that came from the mill discharge with a granulometry larger than 0.147mm is recirculated and the fraction with a granulometry lower than 0.147mm is directed to the silo for bagging.

The three mining companies, installed at Pedra Lavrada – PB, make use of the pebble mill at the respective ore beneficiation plants. These beneficiation units make use of the dry grinding in special situations, where the coating and ball iron contamination are not desired. These systems use others types of coating such as the ceramic and alumina balls or pebbles from the material that is going to be ground (Chaves & Peres, 2010).

For the pegmatite uses in industry, it is necessary to observe certain physical and chemical specifications where better-quality crystals (absence of crystal impurities and defects) are employed in optic and electronic industries, and the lesser quality crystals (presence of crystal impurities and defects) are used in abrasives, ceramics, metallurgical and others industries (Constantine, 1995; Nogueira,1988).

This research seeks to identify and quantify the minerals that are considered to be waste (Figure 1) and are present on the pegmatitic body so that this material can be directed to the correct industry sector and also contribute to minimize the environmental impacts made by mining operations and pegmatite beneficiation. In the development of this research, the characterization and the calculation of work rates (*work index*) of the ore that came from Alto Dois Irmãos-PB artisanal mining were produced before and after the grinding. The characterization contains physical tests to determine the ore relative density, tests of mineralogical identification by X-ray diffraction (XRD), chemical analysis by X-ray fluorescence and morphological analysis by scanning electron microscopy (SEM/EDS).

Figure 1 – Material considered waste in pegmatite mining. Source: Authorship

Therefore, this research achievement contributed to the mineral reserve increase and to the residue generation decrease in artisanal mining and a beneficiation unit, making for increased production, while offering a better-quality porcelain product and probably optics industries.

These product characterizations and experimental conditions that were obtained will also serve as data and technological mineral simulation (software Usim Pac) sources for great grinding process parameters.

1.1 Uses and specifications of quartz crystalline variety

Quartz is used in various industrial areas (civil construction, metallurgical and automotive), and for its use in many cases, it is necessary to go through a comminution process, and in others cases, good technological knowledge (production of cultured quartz and silicon or vitreous silica) is required. This mineral has a broad market and the tendency is to grow due to its application in the areas of computing, energy and telecommunication (Luz & Lins, 2008).

In Table 1, presented are the quartz mineral compositions, in function of their applications (Abdallah, 2010).

Table 1 – Mineral quartz chemical specifications for usage in industry.

Utilization	SiO_2%	Al_2O_3%	Fe_2O_3%	CaO%	MgO%	Grains Sizes
Glasses	99.5	0.1-0.5	0.008	na	-	µm
Optics	99.5	0.1-0.5	0.013	na	low	µm
Ferrossilicon	96	0.4	0.2	low	low	2.54-5.18cm
Refractory Brick	96-98	0.1	-	low	low	-2.36 mm
Sand to Building	80	-	-	Na	na	<20 mm

Source: (Barbosa & Porphírio, 1995 Apud Abdallah, 2010).

2. Materials and methods

The experimental activities to determine the mineralogical composition of the waste that came from quartz extraction. The parameters that enable the environmental impacts minimization and the improvements on the mineral grinding process of the Borborema Pegmatitic Province – BPP, were developed in two stages: Physical tests, and ore characterization.

2.1 Ore relative density

2.1.1 Gas pycnometry

To determine the ore density of this research, tests were done on 03 samples (A, D and F) of the six (06) collected at the comminution circuit and the pycnometry technique with helium gas was used. The equilibrium rate was 0.200 psig/min, approximately 25°C temperature and two purges. The tests were performed at the Mineral Technology Center (CETEM in Portuguese), in Rio de Janeiro and a Micromeriticis brand, model Accupyc 1340 was used.

The procedure to determine the density consists in posteriorly weighing the sample on an analytical balance to measure the real sample volume and calculate the material specific mass. The volume of the solid is defined by the gas absorption of inert helium gas on a solid surface.

2.1.2 Ore characterization

This procedure had the purpose of increasing the surface area of the existent minerals in the sample, to decrease interpolation effects, and to improve mineralogical and chemical readings of the analyzed material. Then the pulverized ore was quartered and forwarded to XRD, XRF and SEM tests.

2.1.3 Scanning Electron Microscopy (SEM)

The mineralogical characterization was done by Scanning Electron Microscopy associated with Energy-dispersive X-ray spectroscopy (SEM-EDS). The tests were performed at the Mineral Technology Center (CETEM) in Rio de Janeiro, and the equipment used was an FEI quanta 400 SEM model, with the system EDS Bruker Xflash 4030.

2.1.4 X-ray diffraction (XRD)

X-ray diffractometry was used to identify the mineralogical stages present in pegmatite ore. The samples were analyzed at the Characterization Laboratory of Academic Unit of Materials Engineering at the Federal University of Campina Grande (UFCG), using the Shimadzu XRD x-ray diffractometer. The radiation used Kα of Cu (40kV/30mA) and the goniometer speed was 2° per minute, in step of 0.02°. The interpretation was made by comparison with patterns contained in an ICDD database.

2.1.5 X-ray fluorescence

The chemical elements presented in the ore sample were identified quantitatively by XRF, using the equipment Shimadzu EDX 720 from the Materials Characterization Laboratory of Academic Unit of Materials Engineering of UFCG. This technique measures the quantity of characteristic x-rays issued by the elements that composed the sample when excited. To do this analysis, the samples were previously compressed into pills with KBr.

2.1.6 WI Determination to ball mill

For the accomplishment of this test, a ball mill is used that operates in dry grinding with a rotation speed of 70 rpm, corresponding to 91.4% of the mill's critical speed, in accordance with ABNT – NBR 11376. This equipment presents measurements of 305 x 305 mm (diameter by length), with rounded corners, smooth coating, rev counter, and automatic stop command.

The test must be performed with a standard feed in granulometry below 3,35 mm. The mass to be grinded in the initial cycle must be equivalent to 700 ml, that can be measured with the help of a graduated cylinder. The granulometric and weighted distributions of the mill's grinding charge and the procedures to determine the variables in the calculation of the WI are described in Luz *et.al.*,2010.

Calculate the WI value according to Equation (1)

$$Wi = \frac{44.5}{Am^{0.23} \cdot Mob.^{0.82} \cdot \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)} \times 1.102 \quad (1)$$

Where: Am = test sieving mesh opening (µm);
Wi = grindability index to grinding (kWh/t);
P_{80} = sieve opening through which pass 80% of the product mass (µm);
F_{80} = sieve opening through which pass 80% of the feed mass (µm); Mob = average of the three last grindability values in balanced condition; 1.102 = conversion factor of short ton to metric ton.

3. Results and discussion

3.1 Density

The results of the apparent density of the sample determination (ROM, retained on the sieve and granulated product) of the pegmatitic ore comminution circuit from Dois Irmãos, Pedra Lavrada, Paraíba, are presented in Table 2.

Table 2 – Apparent density.

Sample	Mass (g)	Standard Deviation	Apparently density (g/cm³)
A - ROM	6.1693	0.0003	2.6683
D – Retained on the sieve	2.7988	0.0005	2.6618
F – Granulated product	8.2805	0.0004	2.6782

Source: Author.

For sample A (ROM), the density identified was 2.6683 g/cm³ with a standard deviation of 0.0003 cm³. In the case of sample D (pebble mill feed), the density was 2.6618 g/cm³ with a standard deviation 0.0005 cm³. And the sample F (Granulated product in the pebble mill) presented a density of 2.6782 g/cm³ with a standard deviation of 0.0004 cm³. These obtained values are aligned with the theoretical density of quartz that corresponds to 2.65 g/cm³ (Beraldo, 1987).

Also, it is possible to verify a small tendency for the relative density to increase (second decimal place) between the ore feed and the grinding product, which can be assigned to tighter packaging, and empty interstice reduction of the thinner ore in the same volume.

3.2 Scanning electron microscopy (SEM)

The Figures of fig.2 present the topographic images of the surfaces obtained by SEM for samples A, D and F.

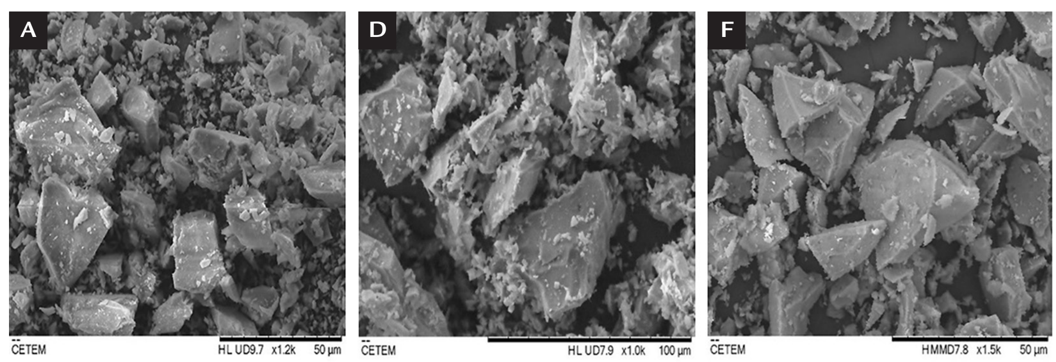

Figure 2 – Topographic images of the surfaces obtained by the SEM, from samples of ROM (A), retained on the sieve (D) and granulated product (F). Source: Author.

The samples A, D and F, by the interpretation of Figure 2, are composed of high purity quartz without accessory mineral interference, contributing to the results expressed in the X-ray diffractograms arranged in the next item. In all of the investigated samples, the quartz particles present irregular morphology with emphasis on the presence of typical conchoidal fracture. The particle granulometry is predominantly below 50µm, being these partially recovered by smaller size debris.

3.3 X-ray diffraction

The diffractograms of samples A, D and F indicated only the presence of quartz for the samples, as expected. Notice the peak coincidences of the three samples' diffractograms, characteristic of the quartz mineral in Figure 3. These results are similar to the results presented by (Luz *et.al*, 2010).

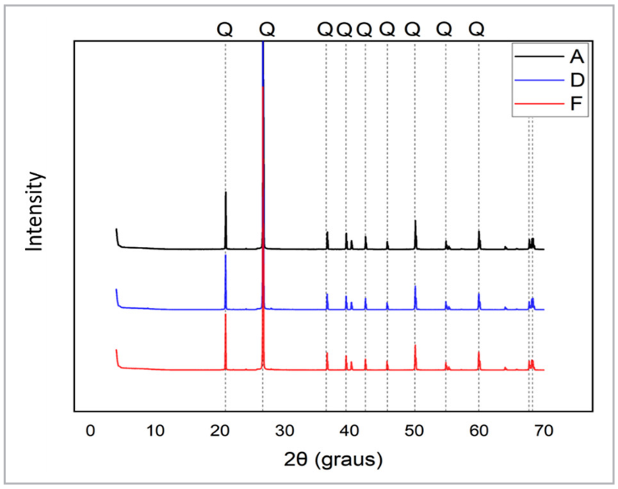

Figure 3 – Diffractograms of samples A, D and F. Source: Author.

3.4 X-ray fluorescence

Table 3 presents the results of the chemical compositions obtained by XRF from the samples Run of Mine (ROM) (A), pebble mill feed (D) and the pebble mill product (F).

Table 3 – ROM samples Chemical composition (A), pebble mill feed (D) and pebble mill product (F).

Samples	Chemical Composition (%)							
	SiO_2	Al_2O_3	SO_3	K_2O	Fe_2O_3	CaO	Ta_2O_5	HO_2O_3
A	92.926	6.318	0.358	0.269	0.069	0.060		
D	94.748	4.507	0.367	0.322		0.055		
F	96.373	2.975	0.355	0.099	0.075	0.058	0.036	0.030

Source: Author.

The XRF results were compared to the literature data presented in Table 1 – Chemical specifications of quartz mineral for industrial use. Notice in Table 3 that the SiO_2 content of the grinding product is 96.37%, so this meets the sand production specifications for civil construction (80%), foundry sand (88-99%), ferrosilicon (96%), and also refractory brick (96-98%). The Al_2O_3 content of sample F was 2.97% (Table 3), which allows the use as foundry sand and colored glass, where the value is variable. About the Fe_2O_3, material F presents a value below 0.2% (0.075%) indicated in the reference (Table 1), allowing its use in pulverized silica and ferrosilicon. The obtained results are within or close to the reference tables, indicating that the waste researched presents quality to be used on industrial scale.

3.5 Determination of *Work Index* (WI)

The resistance of the researched pegmatitic ore, in relation to the comminution process, was identified indirectly by determination of the Work Index. Table 4 presents the reference of Work Index (WI) values, and Table 5, the parameters and calculated values in the performed tests. The operational activities of the tests were directed to a control mesh of 0.147 mm (100 # Tyles).

Table 4 – Work Index (WI) values classification.

Bond WI (KWh/t)	Resistance to break
7-9	Low
9-14	Average
14-20	High
>20	Very High

Source: adapted of (Napier-Munn *et.al,* 1996).

Table 5 – Work Index (WI) test of the researched ore.

Sample	Mesh (mm)	F80 (mm)	P80 (mm)	Gpb g/rotation	WI kWh/t	Tenacity
Milky Quartz	0.147	1.695	0.129	1.503	15.9	High

Source: authorship.

From the test, a value of 15,9Kwh/t was obtained for the grinding of the researched ore. The determined index is close to the suggested values (Beraldo, 1987). According to Table 4, the result of the WI test (15.9) is between 14 – 20, characterizing the studied material as *high resistance to break*. This information is essential for the correct sizing (length x diameter) of the mill, allowing balanced energy consumption in the grinding process.

3.6 Energy determination to grinding in pebble mill

For the sizing of the pebble mill, it is necessary to determine the required energy to pegmatitic ore grinding. Consequently, the Bond method was used.

The Bond method is based on the equation developed by himself and in the value of Work Index – WI (Table 5). The Bond law is widely used through the following equation:

$$E = 10\,WI\left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{F}}\right) \quad (2)$$

Where: E = Necessary energy to the grinding of a short ton (*shor ton*, st = 907kg) of ore in study; KWh/st; WI = Work Index; KWh/st; P_0 = Product granulometry in which 80% passes by a determined reference sieve; in µm. F = Feed granulometry in which 80% passes by a determined reference sieve; in µm. Next will be presented the information that is considered fundamental to define the correct energy for the grinding process and the equipment sizing.

The sample that is used in the grinding process is the pegmatite mining residue (milky quartz); 2.0ton/h in a closed circuit with pneumatic hydrocyclone; work index (WI) = 15.9; feed (F) of ≤ 10 mm or 10.000 µm; and product (P) ≤ 0.147 mm or ≤ 147 µm (≤ 100 mesh)

The mill feed material is coming from an inclined sieve that receives the material from secundary crushing. Energy calculation (Equation 2)

$$E = 10\,WI\left(\frac{1}{\sqrt{147}} - \frac{1}{\sqrt{10{,}000}}\right) = \frac{10\,WI}{\sqrt{P}} - \frac{10\,WI}{\sqrt{F}} = \frac{10x15.9}{\sqrt{147}} - \frac{10x15.9}{\sqrt{10{,}000}} = 11.52 kwh/st$$

The determination of the factors will be done hereafter:

EF_1 = 1,3 (factor that corrects the grinding type, in caso of dry grinding)

EF_2 = it is only applicable in the case of open circuit, that would not be the case.

EF_3 = factor that corrects the mill diameter, it is only determined after the preliminary choice of the mill.

EF_4 = factor that corrects the oversized feed.

$$R_r = \text{reduction ratio} = \frac{F}{P} = \frac{10{,}000}{147} = 68$$

$$F_0 = 4.000\sqrt{\frac{13}{WI}} = 4.000\sqrt{\frac{13}{15.9}} = 3{,}615.52$$ as F > F0 , being Fo a great feed size and F = 10,000, so used is EF_4.

$$EF_4 = \frac{R_r + (Wi - 7) \times \left(F - \frac{F_0}{F_0}\right)}{R_r} = \frac{68 + (15.9 - 7) \times \left(10.000 - \frac{3{,}615.52}{3{,}615.52}\right)}{R_r} = 1.21$$

EF_5 = factor that corrects fineness, in case it is not applicable, used only for extremely thin particle grinding, below 325 mesh (0.044 mm).

EF_6 = not applicable (factor that corrects the reduction ratio for rod mill)

EF_7 = factor that corrects the reduction ratio for ball mill, is given by:

$$EF_7 = \frac{R_r - 1.22}{R_r - 1.35} = \frac{68.0 - 1.22}{68.0 - 1.35} = 1.0$$

EF_8 = not applicable (factor that corrects the inefficiency of the rod mill).

Next, the energy value is defined using the correction factors, initially making up the unit conversions.

Conversion of short ton “short tonnage” to metric ton: Factor = 1.102

Conversion of kw to HP: Factor = 1.341

It is assumed that the energy consume (E) will be:

E = 11.52 kwh/ st, making the due conversions.

E = 11.52 x 1.102 x 1.341 = 17.02 HP.t/h and to 2.0 t/h, there is E = 2.0 x 17.02 = 34.04 HP

Multiplying by the correction factors EF_1,EF_4 and EF_7 , there is E = 34.04 x 1.3 x 1.21 x 1.0 = 53.54 HP of power.

Next, Table 6 was consulted and a mill of 1.83 x 1.83 m of nominal diameter and nominal length, respectively was selected, with a filling percentage of 40% of its volume, and with a motor power of 85HP. Then, EF_3 can be calculated :

$$EF_3 = (8/D)^{0.2} = (8/5.5)^{0.2} = 1.07$$

Where D is the internal diameter to coating in inches.

So, the power corrected by this factor will be: E corrected = 53.54 x 1.07 = 57.28 HP.

Consulting Table 6, it was possible to select a mill that presents the adequate size to attend the power previously determined.

Table 6 – Ball mill characteristics.

Nominal Diameter		Length		Mill Speed			Mill Power (HP)						Diameter (D) internal to coating	
							Discharge by overflow % vol. of charge			Discharge by diphragm % vol. of charge				
m	ft	m	ft	rpm	%Vc	ft/min	35	40	45	35	40	45	m	ft
0.91	3.0	0.91	3.0	38.7	79.9	304	7	7	7	8	8	9	0,76	2.5
1.52	5.0	1.52	5.0	28.2	78.1	399	42	45	47	49	52	54	1.37	4.5
1.83	6.0	1.83	6.0	25.5	78.0	441	30	85	89	93	99	103	1.68	5.5
2.13	7.0	2.13	7.0	23.2	77.2	474	137	145	151	158	168	175	1.98	6.5

Soure: Chaves; Peres (2003).

The Table 7, show the characteristics resume of the determined mill, based on Table 6.

Table 7 – Selected pebble mil characteristics.

Nominal Diameter		Nominal lenght		Mill operation speed			Mill power (HP) and discharge (%)			Coating Internal Diameter	
m	feet	m	feet	rpm	%Vc	ft/min	35	40	45	m	ft
1.83	6.0	1.83	6.0	25.75	78.0	441	-	85	-	1.68	5.5

Source: Chaves and Peres (2003).

At the same time, visits were made to pegmatite beneficiation unities and information about the pebble mill was collected. In Table 8, the information about the grinding equipment is presented.

Table 8 – Current characteristics of pebble mill Mineração Florentino LTDA.

Nominal diameter		Nominal length		Mill operation speed			Power (HP) and discharge (%) of mill			Internal diameter to coating	
m	feet	m	feet	rpm	%Vc	ft/min	35	50	45	m	ft
1.60	5.25	3.50	11.48	150.00	-	-	-	739.74	-	1.43	4.7

Source: Author

When determining the grinding process energy, consequently, it is possible to define and suggest the correct dimensions of the pebble mill (Table 7), and the following measurements were obtained: Nominal diameter of 1.83 m and nominal length of 1.83 m. At the moment, a mill in the beneficiation unit is used with the following measurements: Nominal diameter of 1.60 m and a nominal length of 3.50 m (Table 8). In this case, we found that there is a discrepancy between the equipment that is doing the pegmatitic mineral grinding and the one that was projected correctly. Also, it is possible to observe that the energy necessary for the grinding operations of this material (extraction residue), would be lesser (85 HP – Table 7) than what is being consumed at the present time (739.74 HP – Table 8) in the researched beneficiation unit.

4. Conclusions

From the gas pictometry, the density values were determined for the samples collected at distinct points of the comminution circuit. The average value of 2.66 g/cm³ obtained among the data presented on the tests, is within what was expected, that is a density of 2.65 g/cm³. Confirmation of this result is important to help in sample identification. Another interesting factor is that it can help in choosing the concentration process, in ore volume calculations, and in feed material, tailings and the power plant concentrate.

The results obtained through scanning electron microscopy corroborate with the results obtained by the other characterization methods studied here, presenting only quartz particles, evidenced by the typical microstructural characteristics witnessed in the samples.

Aiming for a better comprehension of

the research material characteristics, XRF and XRD tests were performed. In relation to x-ray diffraction, results showed that the indicated mineralogical stage is from quartz mineral. This information reinforces the idea of working an artisanal mining vein, where this mineral occurs, and then forward it to a comminution process.

The spectrometry of x-ray fluorescence, allowed to perform the chemical analysis of the Run of Mine (ROM) samples, the pebble mill feed and the mill product, which defined the following contents: SiO_2(92.926%), Al_2O_3(6.318%), SO_3(0.358%), K_2O (0.069%), Fe_2O_3(0.069%) CaO (0.060%); SiO_2 (94.748%), Al_2O_3 (4.507%), SO_3 (0.367%), K2O (0.322%), CaO (0.055%); SiO_2 (96.373%), Al_2O_3 (2.975%), SO_3 (0.355%), K_2O (0.099%), Fe_2O_3 (0.075%) CaO (0.058%), Ta_2O_5 (0.036%) and HO_2O_3 (0.030%). These obtained values are within the recommended specifications for several industrial applications (Table 2). These contents indicate that the researched material, which was not previously explored and benefited, represents good quality feedstock and must be taken advantage of, being able to add significant gains.

This material that was not extracted in the mine, can now increase the mineral reserves in the artisanal mining. In relation to beneficiation, it was considered to be without value and then it was seen as residue, accumulating and polluting the environment. Now we can think about residue reduction possibilities that impact the environment. It is also possible to increase production and obtain higher economic values.

A Work Index of 15.9 kwh/t was determined for the waste sample from Pegmatite Alto Dois Irmãos-PB and this index will be fundamental for the grinding equipment (pebble mill) sizing. According to Table 6, this obtained value is considered to be high, and consequently, the studied material is classified as high hardness.

In that regard, the definition of the required energy for grinding this material (residue) showed us that the mill used should have been smaller, and then, we would have an equipment consuming less energy, contributing to soften the Brazilian energy matrix. The correct pebble mill installation would allow to improve the grinding efficacy, increasing production and generating more jobs.

The obtained information from the tests, concerning density, chemical composition, mineralogical, and mainly Bond WI, where it was verified that the studied material has good resistance to grinding, serves to understand the characteristics of the material that is going to be processed. In this case we have a material that has a high degree of purity, ceasing to be seen as a polluter, decreasing significantly the environmental impact, and consequently, increasing the mineral activities profit.

These data can be used to help to change the comminution process flowchart, specifically in the stages of crushing (jaw crusher) and grinding (pebble mill). Posteriorly, this information will be used to optimize the grinding process in Borborema Pegmatitic Province, through mineral simulation.

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