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Development and Validation of a Simplified Laboratory Test to Design Vertical Stirred Mills†

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Abstract

The use of vertical stirred mills in the mining industry has increased remarkably over the past few decades as a result of the growing demand for finer ore grinding. This equipment is recognized to deliver higher energy efficiency in fine grinding operations when compared to conventional tubular mills. Methods of designing vertical stirred mills involve operational experience, pilot plant tests and bench tests. An important issue is that the laboratory-scale test, conducted in the standard 8"×10" jar, requires at least 10–20 kg of material, depending on ore density, which is not available in many cases, particularly in the early stages of greenfield projects. For regrinding of flotation concentrates, several bench scale flotation tests are required to generate such a sample. The paper describes the development and validation with six different ore samples of a simplified laboratory jar mill test using a 6"×8" jar, which is smaller than the 8"×10" size, the latter commonly used which requires about one-tenth of the mass required in the standard test. The proposed test indicated similar results as compared to the standard procedure.

Keywords: grinding, regrinding, jar test, vertical stirred mill, scale-up

1. Introduction

A significant demand for finer grinding has been noticed in several mining projects over the past few decades to achieve adequate liberation, as required for the concentration of valuable minerals. However, the finer the product size, the greater the grinding energy consumption, resulting in an overall increase in operating costs, which may reach or even exceed 50 % of the mineral processing costs (Daniel and Lewis-Gray, 2001; Vieira and Peres, 2013). Comminution technology can have a major impact on subsequent ore concentration stages (Daniel and Lewis-Gray 2001; Marsden, 2009; Napier-Munn, 2012; Pease et al., 2010), which further underlines the importance of proper technology and equipment selection. Appropriate grinding circuit selection and design is thus a key aspect associated with successful mining projects.

Based on these trends, vertical stirred mills with low impeller speed, such as the Vertimill™, has been adopted throughout the mining industry since 1970s (Bergerman, 2013; Goto 2010; Mazzinghy et al., 2017; Toroman and Katircioglu, 2011). These mills consist of a vertical cylindrical chamber in which the charge is stirred by a low-speed impeller. In this paper, it is referred to as vertical stirred mill. Several authors have shown that grinding technology based on impeller stirred mills will be of fundamental importance in minimizing energy consumption in regrind circuits (Bergerman and Delboni Jr., 2014; Hogg and Cho, 2000; Kawade and Schwedes, 1997; Marsden, 2009; Mazzinghy et al., 2017; Napier-Munn, 2012; Norgate and Jahanshahi, 2011; Rule and Neville, 2012; Valery Jr. and Jankovic, 2002).

The design of vertical stirred mill for specific applications are generally based on laboratory tests. Accordingly, Metso, which is one of the main manufacturers of vertical stirred mills, adopts a standard batch grinding test using a 8" (203 mm) in diameter by 10" (254 mm) in length (8"×10") jar (Jankovic and Valery Jr., 2004). The test is carried out according to different grinding times until the target particle size is reached. Such a test provides a relationship between specific energy consumed as a function of particle size, the latter referred as d_{80}. The required energy consumption is thus calculated using such a relationship, based on the target particle size. The specific energy obtained is then multiplied by a factor of 0.65. Such a factor, referred to as the Vertimill™ (VTM) factor, assumes a higher efficiency associated with VTMs (Wills and Finch, 2016). The above described procedure provides a good correlation with industrial mills and is used as an

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industry standard for the design of this kind of equipment (Bergerman, 2013; Wills and Finch, 2016; Donda, 2003; Mazzinghy et al., 2014). The sample required to perform each grinding time is based on the calculated volume required to entirely fill the voids within the steel ball charge, which for the standard tests is 1.381 L. For instance, for a material with a bulk density of 3.04 g/cm^3, such as the iron ore concentrate used in this study, each grinding time will require 4,203 g of sample, which results in a total of 21,105 g for all five grinding times.

A remarkable aspect of designing vertical stirred mills for industrial regrind circuits is the lack of sufficient mass for carrying out batch grinding tests that follow the standard adopted by Metso. This is a serious hurdle for projects in the early stages, as 100–1,000 kg of ore would be necessary to obtain the required amount of regrinding feed. Indeed, in a typical copper sulphide flotation project, a significant amount of rougher concentrate is required for regrind testing. Such a situation becomes even more critical for low-grade ores, where rougher concentrate mass recovery is low as well. One practical consequence is that a number of industrial regrind circuits are designed without any proper laboratory or pilot testing validation. Laboratory batch tests based on significant smaller sample mass would thus be particularly useful for designing vertical stirred mills.

This paper describes the development and validation of a laboratory jar mill test using a 6"×8" jar, requiring much less sample than a standard test, which is carried out with a 8"×10" jar, as described in Mazzinghy et al. (2014) and Wills and Finch (2016). The required specific energy is based on the global specific energy method (Austin et al., 1984). The samples used in our tests represented the respective industrial regrind circuit in all cases.

2. Materials and methods

Tests were carried out with six different ore samples, including copper, phosphate, and iron ores obtained in industrial grinding circuits from Brazil. The surveyed plants were as follows: Anglo American Minas Rio Project (iron ore), Vale Salobo (copper ore), Vale Sossego (copper ore), Mosaic Tapira (phosphate ore), and Vale Vitoria Pelletizing plant (iron ore). Plant flow sheets and operating data may be found elsewhere (Bergerman et al., 2012; Guimarães, 2004; Mazzinghy et al., 2015; Meyer et al., 2015). Each sample was tested to determine the respective density of solids (using a pycnometer), the bulk density by using a graduated measuring cylinder, and the particle size distribution and specific surface area by laser scattering using a Malvern 2000 Mastersizer. Deionized water was used as a dispersion medium in the analysis carried out using Malvern. The refraction indexes of particles were 1.45, 1.729, and 1.627, respectively for copper, iron, and phosphate ores, while it was 1.33 for the dispersion medium. The Malvern analyser stirrer speed was 2,500 rpm and ultrasound was applied for one minute.

After the initial ore characterization tests, each sample was quartered for grinding in both 6"×8" and 8"×10" jars according to test conditions listed in **Table 1**. Both mills were fitted with smooth stainless-steel liners.

Table 1 Test conditions for each jar test.

Conditions and Characteristics		6"×8" jar	8"×10" jar
Jar volume (m^3)		0.0037	0.0082
Ball filling, J (%)		42	42
Charge voids (%)		40	40
Grinding ball size (mm)		12.7	12.7
Solids (%)		70	70
Charge interstice filling, U (%)		100	100
Sample mass for each grinding cycle (g)	Anglo American Minas Rio	1,883	4,203
	Vale Salobo	1,306	2,914
	Vale Sossego—sample 1	1,386	3,094
	Vale Sossego—sample 2	916	2,044
	Mosaic Tapira	1,145	2,555
	Vale Vitoria	1,838	4,102
Mill speed (rpm)		82.5	71.4
Mill rotation speed (% critical speed)		76.0	76.0

Fig. 1 illustrates the laboratory mill used in all tests. Five grinding times were carried out for each sample according to standard periods of 5, 10, 20, 40, and 80 minutes. A fresh sample was used in each grinding time.

Additional tests were carried out with the sample of Salobo ore, for which a larger mass was available. In this case, the same initial sample was ground according to the stipulated five grinding periods. Although it is a time-consuming test, as size analysis is required in between consecutive grinding times, such a procedure reduces the required sample to one-fifth of the standard test.

The jar mill power consumption was measured by a torque meter (**Fig. 1**), and results were compared to estimates using the equation proposed by Rowland Jr. (1986) (Eqn. 1), which applies to jars with a diameter smaller than 2.44 m.

$$kW_b = 6.3D^{0.3}\sin\left(51-22\left(\frac{2.44-D}{2.44}\right)\right)\times$$
$$\left(3.2-3V_p\right)C_s\left(1-\frac{0.1}{2^{(9-10C_s)}}\right) \quad (1)$$

where:

kW_b = mill power per metric tonne of balls (kW/t)
D = mill diameter inside liners (m)
V_p = fraction of mill volume loaded with balls (%)
C_s = fraction of critical speed (%)

The product particle size distribution, density, and mill power error was determined through five repeated measurements of the same sample/test and the respective standard deviation was determined. Details of all error calculations are described in Bergerman (2013). The assessment procedure adopted indicated that the error associated with the mill power calculation was very low (below 1 %, thus not represented in the error bars of the graphics presented in the paper), whereas the particle size (d_{80} and specific surface area) error was approximately 5 %, which is the value used at the error bars in **Figs. 3–10**.

Fig. 1 8"×10" jar mill equipped with a torque sensor.

3. Results and discussion

The results obtained in the characterization tests are described in **Table 2** and **Fig. 2**.

The d_{80} of the samples varied from 69 to 166 µm, while their bulk density varied from 1.48 to 3.04 g/cm^3. The values varied within a relatively wide range for both d_{80} and bulk density, which was here considered instrumental for validating the proposed regrinding test.

Figs. 3 to **8** illustrate the d_{80} and specific surface area parameters, as well as specific energy consumption, calculated with Eqn. (1), for the different grinding times and

Table 2 True and bulk densities of tested sample.

Sample	Density of solids (g/cm^3)	Bulk density (g/cm^3)
Anglo American Minas Rio	5.03 ± 0.08	3.04 ± 0.03
Vale Salobo	3.63 ± 0.02	2.11 ± 0.04
Vale Sossego —sample 1	3.68 ± 0.01	2.24 ± 0.01
Vale Sossego —sample 2	2.98 ± 0.05	1.48 ± 0.02
Mosaic Tapira	3.15 ± 0.04	1.85 ± 0.01
Vale Vitoria	4.79 ± 0.15	2.97 ± 0.01

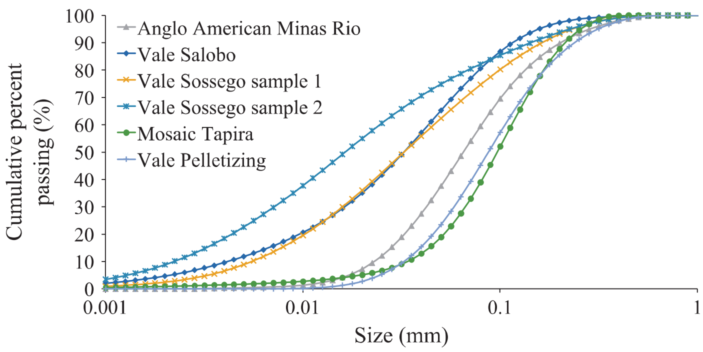

Fig. 2 Particle size distribution of grinding test feed samples.

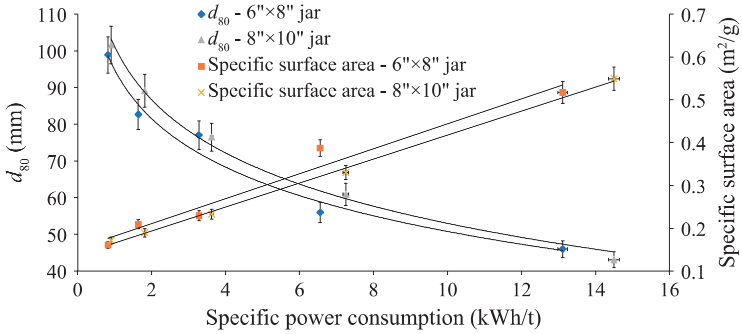

Fig. 3 Specific power consumption as a function of d_{80} and specific surface area—Anglo American Minas Rio sample.

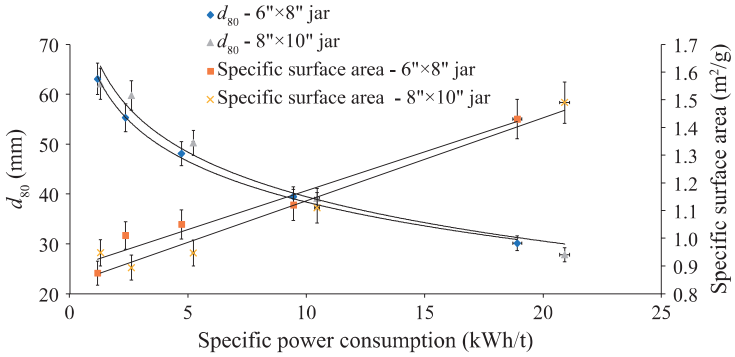

Fig. 4 Specific power consumption as a function of d_{80} and specific surface area—Vale Salobo.

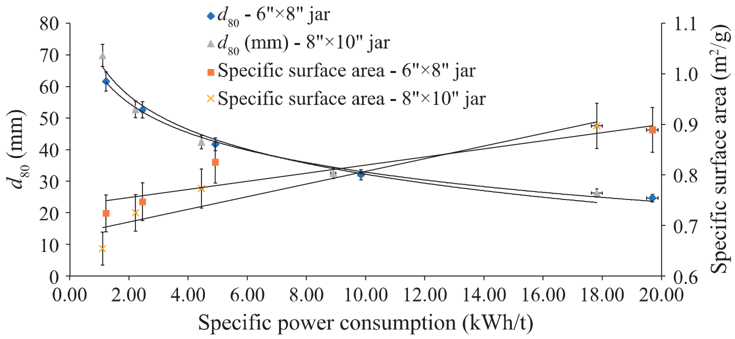

Fig. 5 Specific power consumption as a function of d_{80} and specific surface area—Vale Sossego sample 1.

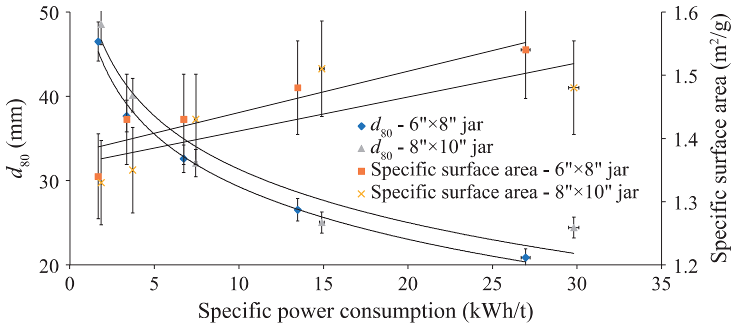

Fig. 6 Specific power consumption as a function of d_{80} and specific surface area—Vale Sossego sample 2.

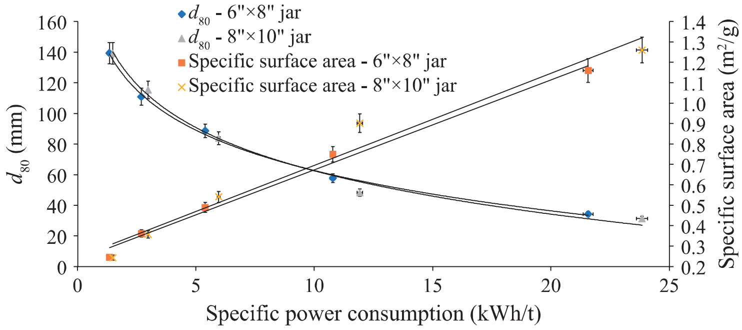

Fig. 7 Specific power consumption as a function of d_{80} and specific surface area—Mosaic Tapira sample.

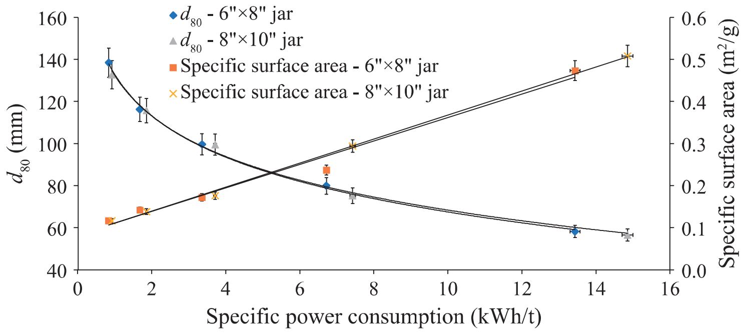

Fig. 8 Specific power consumption as a function of d_{80} and specific surface area—Vale Vitória sample.

Table 3 Jar test results in both mills for different selected specific energies (10 and 20 kWh/t).

Sample	Jar	10 kWh/t		20 kWh/t	
		d_{80} (μm)	Difference (%)	d_{80} (μm)	Difference (%)
Anglo American Minas Rio	6"×8" 8"×10"	50.8 53.0	4.2	37.5 38.5	2.5
Vale Salobo	6"×8" 8"×10"	38.4 39.5	2.8	30.2 30.5	1.2
Vale Sossego—sample 1	6"×8" 8"×10"	32.8 32.2	2.0	23.4 21.5	9.1
Vale Sossego—sample 2	6"×8" 8"×10"	29.3 31.4	6.6	23.0 25.0	7.9
Mosaic Tapira	6"×8" 8"×10"	62.7 62.5	0.3	36.3 34.2	6.2
Vale Vitoria	6"×8" 8"×10"	67.5 68.3	1.3	47.8 49.0	2.6

jar dimensions.

Regression carried out in each graph indicated generally good fitting for both d_{80} and specific surface area as a function of specific energy consumption. Such observation was valid for both jars used in tests i.e., the standard 8"×10" and the proposed 6"×8". The results obtained for the different jars are very similar, with small differences within the errors related to the measurements. Larger differences between the jars appeared only for Vale Sossego sample 2. One possible explanation is that, for this sample, the feed was already very fine and the extent of size reduction obtained was very limited for the grinding times studied.

In order to compare the results for both tests in two different specific energy consumptions, **Table 3** compares the results of the jar tests in both mills for 10 and 20 kWh/t.

The results focus on product d_{80}, which is the reference parameter for vertical stirred mill design and selection.

The data shown in **Table 3** illustrate that the results are very similar, with less than 10 % difference between the d_{80} obtained for the different jar sizes. In fact, differences in absolute terms were within the ± 2 µm, which is considered very small. This can be explained as the two tests conditions, for both 6"×8" and 8"×10" jars, have similar parameters, which includes same ball size, critical speed, length to diameter ratio (1,33 for the 6"×8" jar and 1,25 for the 8"×10" jar) and power per volume unit (5,0 kW/m^3 for the 6"×8" jar and 5, 6 kW/m^3 for the 8"×10" jar).

Figs. 9 and **10** and **Table 4** illustrate the variation of d_{80} and specific surface area parameters as a function of specific power consumption for different grinding times, using only one sample (o.s.) for all grinding periods. In this case, the material from the first grinding time was placed back in the mill for the second grinding time and so forth.

The results indicate no significant differences between the standard test procedure and the proposed one, i.e., regrinding the initial sample in the different grinding periods. It also shows the same magnitude of errors, in spite of the additional sample manipulation involved with the size analysis required between grinding times.

Based on such results, one can consider any one of the tests, standard or simplified, as a basis to design vertical

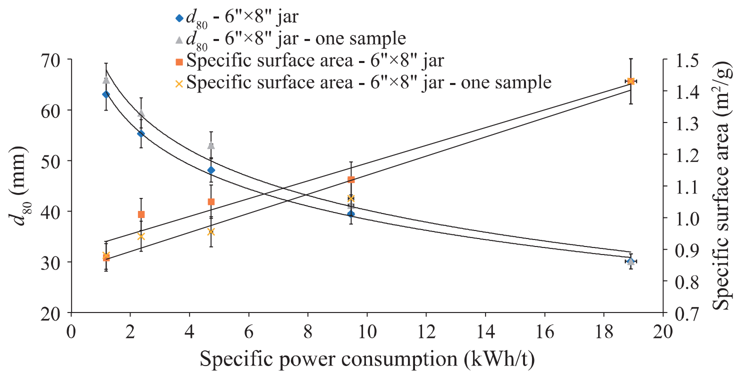

Fig. 9 Specific power consumption as a function of d_{80} and specific surface area—one sample per grinding time vs. one sample for all grinding times - 6"×8" jar—Vale Salobo sample.

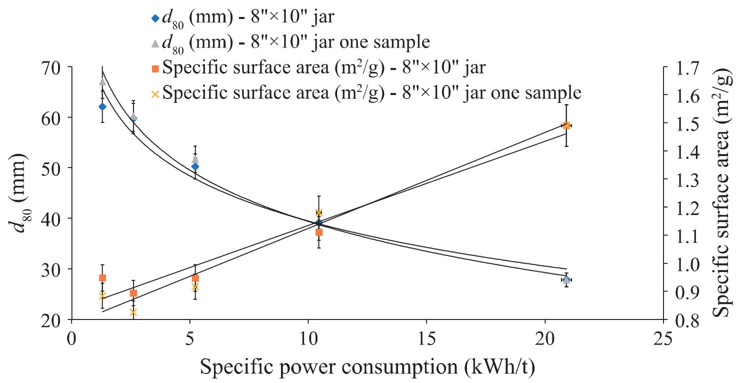

Fig. 10 Specific power consumption as a function of d_{80} and specific surface area—one sample per grinding time vs. one sample for all grinding times - 8"×10" jar—Vale Salobo sample.

Table 4 Jar test results in both mills for different selected specific energies (10 and 20 kWh/t).

Sample	Jar	10 kWh/t		20 kWh/t	
		d_{80} (µm)	Difference (%)	d_{80} (µm)	Difference (%)
Vale Salobo one sample	6"×8" 6"×8" o.s.	38.4 40.2	4.6	30.2 31.2	3.4
Vale Salobo one sample	8"×10" 8"×10" o.s.	39.5 39.4	0.2	30.5 29.2	4.4

stirred mills. The required sample mass is, however, the great difference between the tests. In the case of Anglo American Minas Rio ore, the sample required for the standard test was 21,015 g, as opposed to 9,165 g for the simplified test. Such requirement would be reduced to 1,883 g if one considers the regrind of the same sample in each grinding period. Moreover, considering the average mass recovery of approximately 47 % at this mineral processing plant, the mass of material to be floated in a laboratory study could be reduced from 45 to 4 kg. When considering sulphide ore, such as Vale Salobo, where the mass recovery of the rougher stage is around 10 %, the mass of material to be floated in a laboratory test campaign would be reduced from 146 to 13 kg, in order to obtain the 1,306 g required for the simplified jar test.

4. Conclusions

The study demonstrated the possibility of using significantly less sample mass in the test currently used for designing vertical stirred mills. The results of the proposed 6"×8" jar test showed a difference of only ± 2 μm in the product d_{80}, as compared to corresponding results obtained from tests carried out according to standard Metso 8"×10" jar test. This can be explained as the two tests conditions, for both 6"×8" and 8"×10" jars, have similar parameters, which includes same ball size, critical speed, length to diameter ratio and power per volume unit. The sample requirement of the proposed test is less than half that of the standard test. The sample requirement may be reduced to one tenth of that required in the standard test if the regrind of the same sample in the each grinding period procedure is adopted. The difference is quite significant especially in early development stages of a project. In such situations the mass of available ore is small. Other sample limitations include projects involving low-content metallic ores, which require flotation tests to be carried out at low mass recovery rates to generate enough regrinding mass feed. In both cases, the proposed test method is an adequate alternative to assess the energy required by the regrinding process.

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Nomenclature

kWb	Mill power per metric tonne of balls (kW/t)
Cs	Fraction of critical speed (%)
D	Mill diameter inside liners (m)
d_{80}	Diameter of 80 % passing sieve size (μm)
Vp	Fraction of mill volume loaded with balls (%)

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Homero Delboni

Dr. Homero Delboni, Junior graduated in Mining and Minerals Processing Engineering from the University of São Paulo. In 1989, he obtained a M.Eng. degree in Minerals Engineering at the same university. He joined the Julius Kruttschnitt Mineral Research Centre of the University of Queensland, Australia, where he obtained his PhD degree in 1999. He is currently a Lecturer in the Department on Mining and Petroleum Engineering at the University of São Paulo, where he is involved in both teaching and research in mineral processing, particularly in comminution.