The Geopyörä breakage test for geometallurgy

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ABSTRACT

Comminution tests are an essential element in the design of ore beneficiation plants. Many methods have been developed to assess the breakage characteristics of rocks to generate parameters for modelling. However, most of the existing methods are laborious, expensive and require large samples. Consequently, test work has been traditionally conducted with a few representative reference samples. On the other hand, geometallurgical modelling programs require an extensive amount of test work to allow understanding the variability of ore properties within the deposit and establish spatial geometallurgical domains that show the differential responses to mineral processing. Therefore, comminution tests for geometallurgy need to be more efficient in terms of time, cost and sample size. This paper introduces a new testing device (Geopyörä) which is capable of measuring forces and energy applied to rock particles during the breakage process. The new testing method uses smaller samples and can be up to 50 times faster than other commonly used tests in the industry. This paper presents the concept prototype and the preliminary test work results, which have been benchmarked against some of the industry standard tests, such as the JK Drop Weight Test (JKDWT), the SMC Test® and the Bond ball mill test.

Keywords: Geometallurgy, comminution, ore breakage characterization, variability.

1. Introduction

Ore variability has been a widely studied topic that seeks to improve efficiency in running operations and to diminish the uncertainty in feasibility studies. In this context geometallurgy is a discipline that complements design and operation approaches by providing constraint inputs that give information about the geological variability and how this affects the metallurgical performance. There are two common leading root causes of faults in mill designs: the selection of wrong design criteria and the use of reduced design methodologies or inaccurate models. The selection of wrong design criteria occurs mainly due to lack of quality test work or misinterpretation of results and orebody variability (Bueno *et al.*, 2015).

Geometallurgy adds parameters to the typical block model used in geostatistics by incorporating data to create an integrated view of the economic optimization in mining operations (Van den Boogaart, 2018). Geometallurgical models include ore hardness, energy consumption, mineral liberation, recovery and metallurgical performance among others as parameters. Strong relationships between easily obtainable test measures and metallurgical performance predictions are crucial to improve the overall mine performance (Lund & Lamberg, 2014). Within the framework of a mine it is important to understand that comminution represents the highest energy consumption in the mining industry with a 36% of the total (Valery *et al.*, 2019) Ballantyne and Powell (2014)

In terms of comminution measurements for geometallurgical purposes, Mwanga *et al.* (2015) described an optimal test as one that should be simple, repeatable, easy to execute, with a maximum time of execution of 1 hour and that uses less than 0.5 kg of samples. This optimal test should measure both crushability and grindability parameters that could be directly used in modelling and simulation of comminution circuits. Additionally, this test should also be simple to include mineral liberation information.

Hardness and breakage characterization tests can be divided into four major categories: grinding, single-particle breakage, bed breakage and rock mechanics tests. Several authors such as Powell and Morrison (2007), Mwanga *et al.* (2015) and Lois-Morales *et al.* (2020) have highlighted the necessity of developing tests that are capable to address those four groups and obtain as much information as possible with a single test.

The scope of geometallurgical programs depends on multiple factors, such as: resource size, number of geological domains, flowsheet complexity, ore and metallurgical variability among others. The number of tested samples required to obtain a good understanding of ore variability has been discussed on several occasions. Morrell (2011) differentiated pre-feasibility studies, which require only few samples, and geometallurgical programs aiming to forecast daily comminution throughput, where the number of samples can increase by at least one order of magnitude. Al Ruiz *et al.* (2009) highlighted that for a robust model to describe a comminution circuit performance, the identification and selection of sufficient and relevant samples is essential.

Morell (2011) emphasized that keeping costs at a minimum is an important criterion for developing an optimal comminution test for geometallurgy, allowing a higher number of samples to be tested with a similar budget when compared to traditional testing. David (2019) suggested two stages for estimating the number of samples required to understand the ore-body variability: the first is to estimate the degree of variability of the deposit by testing a sufficient number of samples; and the second is to test an adequate amount of samples to validate the confidence needed for design and simulation purposes.

Depending on the deposit, an optimal number of tests must be conducted to measure ore properties both in terms of competency and hardness. Ore competency is usually described by parameters such as the JKDWT Axb, SMC Test® DWi (Drop Weight Index) or SPI (SAG Power Index), while hardness is typically measured with the BWi (Bond Work Index). Competency is directly related to SAG mill throughput, while hardness has a strong influence on ball mill specific energy and grind size. These differences are essential when designing SAB (SAG and ball mill) or SABC (SAG and ball mill with-pebble crushing) grinding circuits. To achieve an accurate prediction of mill throughput and grind size fluctuations the variability analysis must be thorough, while the criteria to adopt the 80th percentile of the ore properties as a design value is not the best approach to account for feed variability (Bueno *et al.,* 2015).

This paper presents a new breakage test device and method, which are ideal for geometallurgical applications. The Geopyörä can rapidly test small discrete samples, either bulk or drill cores. The short testing time results in low operating costs, which allows many samples to be tested for a better understanding of the ore variability. The validation results showed that the test is capable of measuring both competency and hardness parameters with high accuracy and precision.

2. Experimental

2.1. Geopyörä device

The Geopyörä (patent pending - PCT/FI2020/050100) is a comminution testing device capable of performing reliable breakage characterization of small samples, in short time and low cost, aiming to be an optimal test for geo-metallurgical purposes (Chavez Matus, 2020). The concept was developed by Marcos Bueno and Rajiv Chandramohan during PhD studies at the JKMRC, SMI of University of Queensland when considering the shortfalls of existing testing techniques. The prototype was developed at the University of Oulu and consists of two instrumented wheels of 600 millimetres diameter each, with an adjustable gap as shown in Figure 1. The steel wheels are powered by integrated electric motors placed in the frame and the available kinetic energy on the wheels range from 100 to 250 Joules according to speed. The device provides data of the compression force and measures the loss of rotational moment to determine the energy required for each particle breakage event (Torvela, 2020).

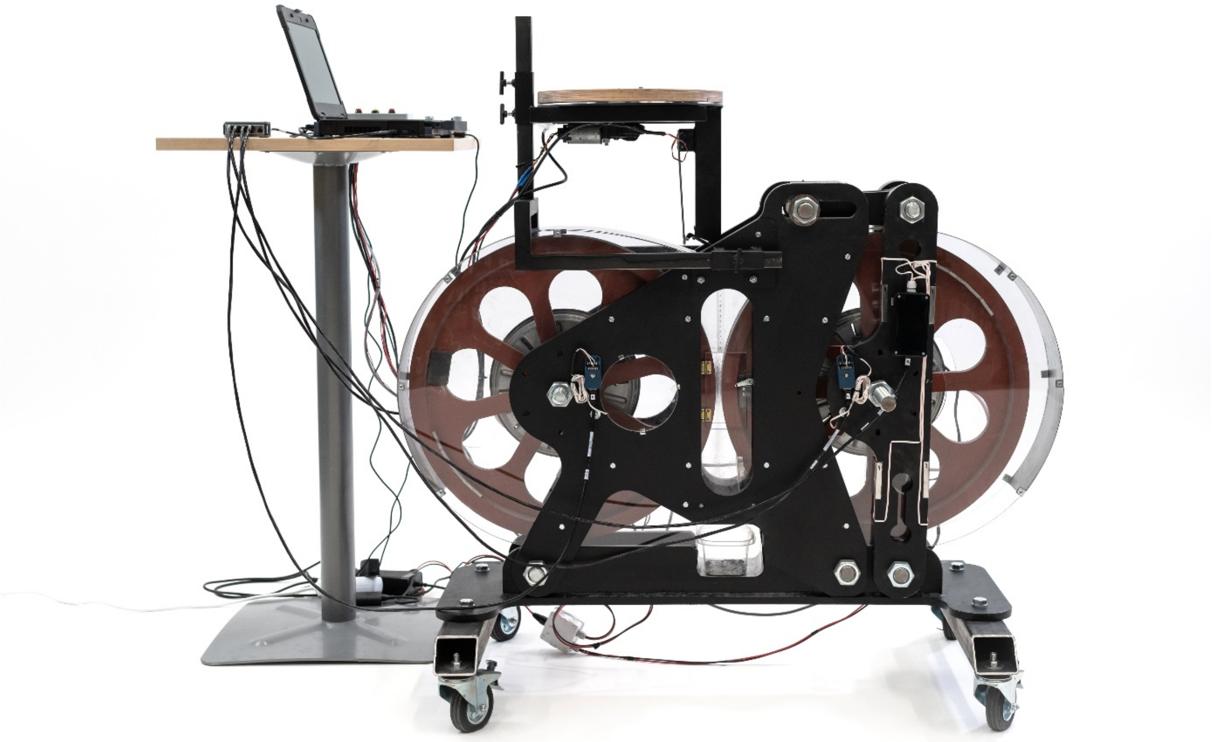

Fig. 1. Geopyörä device

The device can use both bulk and drill core samples. The Geopyörä has been tested by using half of a one-meter long section of drill core to develop a procedure that can efficiently work with samples obtained during exploration for geochemical assaying purposes. This procedure ensures that half core is used for the breakage test, while the other half can be kept in archive or used for other purposes. The product of the breakage test can also be used for geochemical or other analyses when required. For bulk samples, one kilogram of material with a particle size range of 8 to 45 mm is sufficient for the test.

A minimum of two sets of 15 particles in a narrow size fraction are required, one for high and another for low specific energy level. The energy levels are adjusted by modifying the gap between the two wheels. However, it should be noted that unlike most other tests the energy is not an input parameter but a response of the degree of reduction. The device has been tested with particles ranging from 31.5 to 8 millimetres. However, for the validation procedure, particles of 22.4 x 19 mm were used. Particles are placed on an automatic feeder, which drops them from the top of the device to the crushing zone between the two rollers one at a time. The instrumentation and CPU record the force and energy data for each breakage event. After crushing, the product is collected in a tray at the bottom of the equipment. This procedure was established so that the test can be reproducible and operator-induced bias is minimized.

2.2. Sample preparation and development of a methodology

Bulk and drill core samples from six mines located in Finland, as shown in Table 1, were used to develop and validate a methodology for the Geopyörä test. The amount of ore used for the validation tests was approximately 250 kg per mine.

Table 1.
Ore samples description.

	Deposit type	*Sample type*
Mine A	Gold ore	Bulk and Drill core
Mine B	Polymetallic ore	Bulk and Drill core
Mine C	Nickel – Zinc ore	Bulk
Mine D	Polymetallic ore	Bulk and Drill core
Mine E	Phosphate ore	Bulk
Mine F	Silver – Zinc ore	Drill core

Each sample was crushed, sieved and separated in narrow size fractions from 63 mm to 8 mm. Sub-samples were prepared for JKDWT, SMC test® and Geopyörä test. The JKDWT and SMC test were conducted at the Wardell Armstrong centre, the crushed samples were returned to the Oulu Mining School (OMS) facilities, where the final product sieving was conducted. The sieved samples were further crushed until all the material passed 3.35 millimetres to meet the feed size criteria of the standard Bond ball mill test (Bond, 1961). Bond tests were performed on each sample, with a closing screen aperture of 150 µm.

For the bulk sample validation, three sets of 22.4 x 19 mm particles per mine were tested at three different energy levels, which were modified by changing the gap to particle size fraction. Gap fractions of 25%, 50% and 75% were used in this research.

Fifteen meters of NQ and BQ (diameter of 47.6 mm and 36.4 mm respectively) drill core from each mine were used in core sample preparation, where one-meter sections were individually pre-crushed and sieved to obtain particles for testing. In order to develop a methodology that generates enough particles in the operational particle size range, core samples were prepared using a jaw crusher with gap apertures ranging from 23 mm to 8 mm. Figure 2 shows the distribution of the number of particles obtained in different size classes for eight different crusher gap settings.

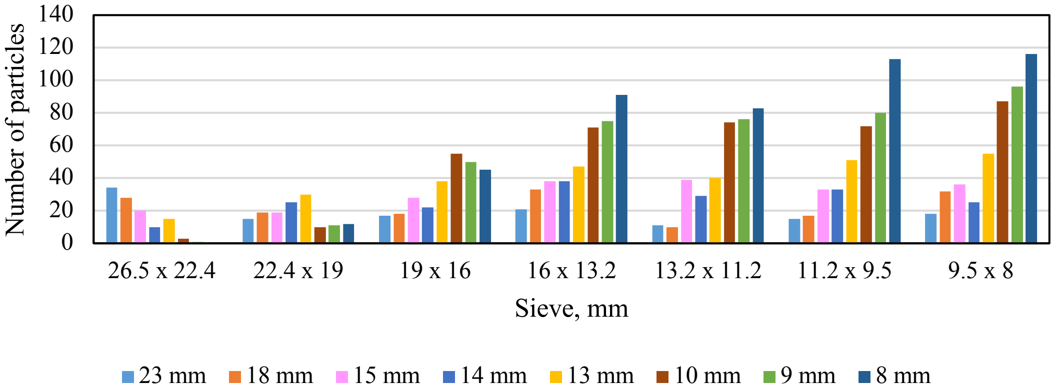

Fig. 2. Drill cores particle distributions after jaw crushing at a range of gaps

The optimum gap setting for the crushing stage was determined with a simple binary logic decision matrix, which checks if there were more than 30 particles in a size fraction or not (i.e. 1 or 0), as shown in Table 2. This criterion ensures that a minimum of two sets of 15 particles are obtained for testing, one at low and another at high energy setting. The optimal pre-crushing gap aperture was found to be 13 millimetres because it generated enough particles in six different size classes which are suitable for the breakage test.

Table 2.

Decision matrix to determine the optimal gap opening of the pre-crushing

	Crusher gap opening (mm)							
Size (mm)	23	18	15	14	13	10	9	8
26.5 x 22.4	1	0	0	0	0	0	0	0
22.4 x 19	0	0	0	0	1	0	0	0
19 x 16	0	0	0	0	1	1	1	1
16 x 13.2	0	1	1	1	1	0	0	0
13.2 x 11.2	0	0	1	0	1	0	0	0
11.2 x 9.5	0	0	1	1	1	0	0	0
9.5 x 8	0	1	1	0	1	0	0	0
Sum	**1**	**2**	**4**	**2**	**6**	**1**	**1**	**1**

3. Results and discussion

3.1. Geopyörä and JKDWT comparison

Bulk samples of five different mines were tested both in the Geopyörä device and JKDWT. The mass-specific energy of the breakage in the Geopyörä was calculated as a function of the measured average energy and the total sample set mass. The cumulative mass percentage of the product passing 1/10th of the initial particle size, t_{10} was measured for each test. The specific energy values ranged from 0.11 to 1.35 kWh/t for the various tested samples, as shown in Table 3 where the maximum and minimum values obtained for six different particle sizes are presented.

Table 3.

Specific energy ranges.

Particle size (mm)	*High Energy (kWh/t)*	*Low Energy (kWh/t)*
22.4 x 19	0.81	0.11
19 x 16	1.25	0.28
16 x 13.2	0.8	0.34
13.2 x 11.2	1.35	0.12
11.2 x 9.5	0.78	0.52
9.5 x 8	0.92	0.24

The maximum value, 1.35 kWh/t, is almost half of the highest energy value in the JKDWT test. Since the Geopyörä design aims for a single impact, allowing for fragments of broken particles to pass freely through the gap without further breakage, this is a clear indication that the high energy levels used in the JKDWT and SMC test® are providing more energy than required to break the particles. Previous studies have shown that at high energy levels (2.5 kWh/t), the JKDWT is causing secondary breakage or even compressing the fragments into a cake (Chandramohan, 2013)

The JKDWT Axb is a recognized metric of ore competency in the mining industry and is widely used in comminution modelling. Equation (1) shows the mathematical relationship between breakage index (t_{10}) and comminution specific energy (Ecs) that is used to fit A and b parameters to a data set (Napier-Munn *et al., 1996*). The A and b parameters fitted to the Geopyörä experimental data were compared against the official JKDWT Axb values as reported by JKTech. Figure 4 shows the good agreement between the JKDWT and the Geopyörä Axb.

$$t_{10} = A\left(1 - e^{-b \cdot E_{cs}}\right) \qquad (1)$$

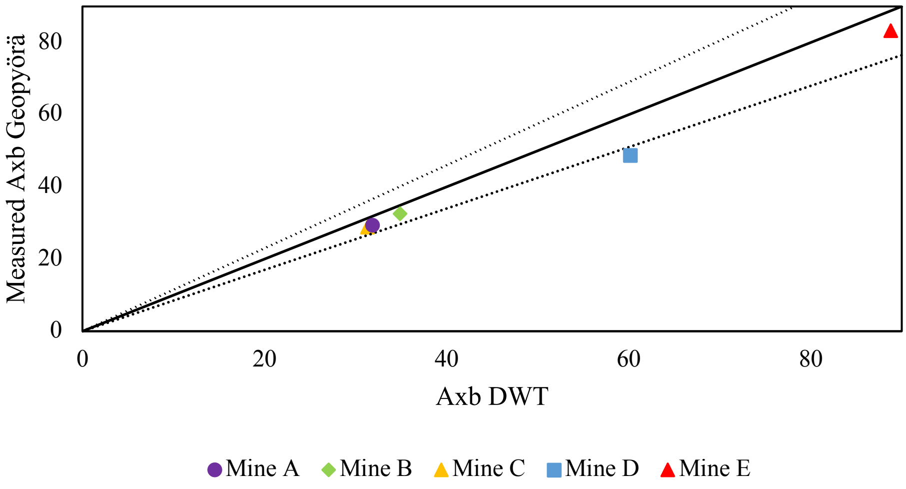

Fig. 4. Comparison of Axb parameter measured with the standard JK drop weight test and the new Geopyörä test

It is worth mentioning that the highest specific energy measured by the Geopyörä test in these sample sets was 1.18 kWh/t while the JKDWT has data in a higher energy point of 2.5 kWh/t, and that the fitting was conducted with three points per ore in one particle size while the JKDWT uses 15 points in 5 particle sizes. Despite these differences, the Geopyörä breakage data was sufficient to provide a good fit of A and b parameters.

There is also a possibility to simplify the Geopyörä procedure by using only two energy levels rather than three. To evaluate the impact of this simplification in the quality of the results, Table 3 compares the Axb parameter fitted using 3 and 2 energy levels against the JKDWT results to evaluate the relative error between these two methods. The results show that the average relative error of the Axb fitted using 3 energy levels is 1% lower than using only 2 data points, with the highest difference observed in the softest ore (Mine E). Since the difference is marginal, it can be concluded that the Geopyörä test is capable of deriving reliable Axb parameters with a straightforward procedure, which requires only two breakage energy levels and a single particle size.

Table 4.

Axb result comparison between DWT and Geopyörä analysis.

	A x b			*Relative error (%)*	
	DWT	3 Energy levels	2 Energy levels	3 Energy levels	2 Energy levels
A	31.9	29.9	29.4	6.8	7.6
B	34.9	32.3	32.5	7.5	6.8
C	31.3	28.8	29.0	8.2	7.4
D	60.2	48.6	50.1	19.2	16.8
E	88.8	83.3	75.4	6.2	15.1

To further assess the consistency between the two devices, the fragmentation (t10) obtained at equal specific energy (Ecs) levels in each test has been compared. However, equivalent t_{10} values had to be calculated for the JKDWT using the same Ecs values as measured by the Geopyörä which does not necessarily match the nominal Ecs values used in JKDWT. Therefore, Equation (1) was used to calculate the equivalent t_{10} values with A and b parameters obtained in the JKDWT and for each sample. A consistent agreement between the t_{10} values measured with Geopyörä and calculated using JKDWT Axb for the same Ecs, was obtained as shown in Figure 3. The correlation shows data of five different ores using particles of 22.4 x 19 mm size. Each ore sample was tested at three energy levels provided by gap fractions of 75% 50% and 25% of the geometric mean particle size.

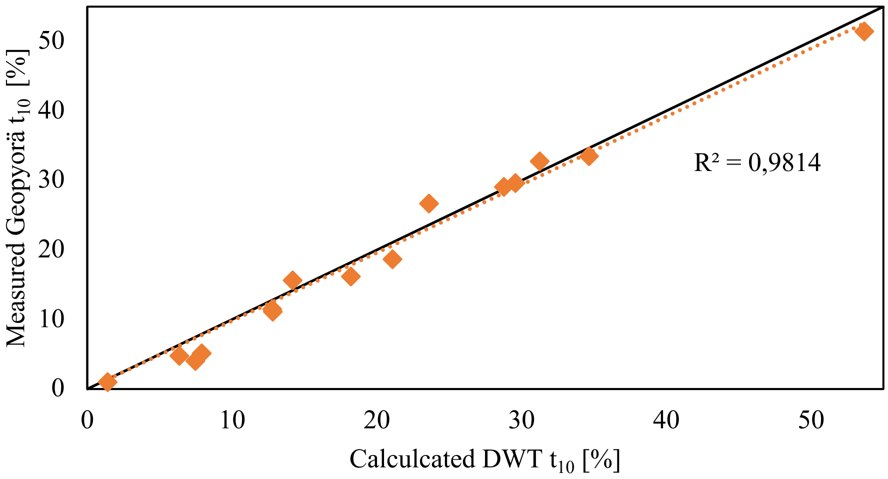

Fig. 3. Comparison of the calculated DWT t_{10} and the measure t_{10} of Geopyörä test

3.2. SMC Test® DWi

Another widely used metric to measure competency is the Drop Weight Index DWi, which is obtained from the SMC Test®. This test has a data base of more than 35,000 measured samples from more than 1,300 ore bodies (Morell, 2015). To calculate the Drop Weight Index in order to compare it with that reported by the SMC test, Equation (2) was used (Doll, 2016).

$$DWi = \frac{SG \cdot 96{,}703}{(Axb)^{0{,}992}} \tag{2}$$

The Geopyörä Axb values used in these parameters were fitted using two energy values, as described in Table 4. The specific gravity values are show in Table 5.

Table 5.

Specific gravity values.

	Mine				
	A	B	C	D	E
SG	2.95	3.2	2.98	2.9	2.8

Figure 5 shows consistency between the DWi results and the Geopyörä estimated DWi. Dashed lines show a dispersion range of ± 20%; four of the five samples are within this range.

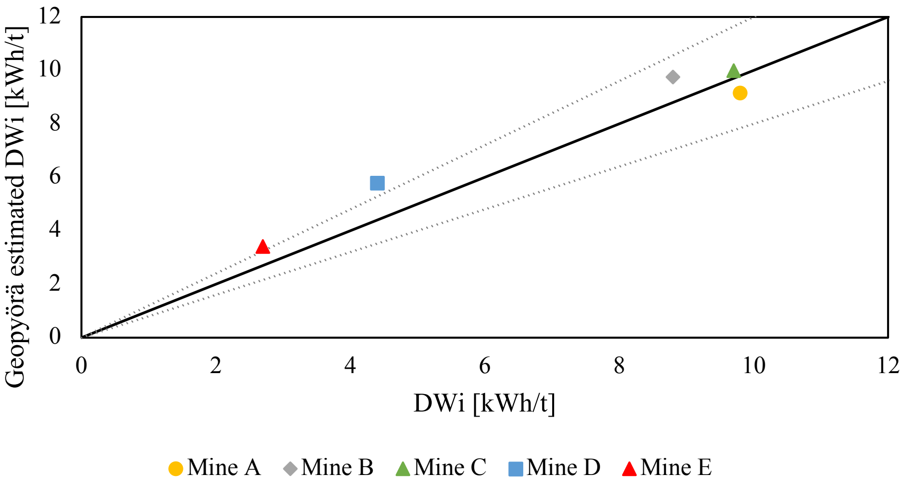

Fig. 5. Comparison between DWi and Geopyörä calculated DWi

3.3. Bond Ball Mill Work Index

Standard Bond ball mill tests were performed to determine the Bond Ball Mill Work Index (BBMWi) for each sample. The results were compared to BBMWi values estimated using the Geopyörä data; named the Bond_{GP} value. The BBMWi was estimated using the measured specific breakage energy and the amount of product passing a closing screen aperture used in the Bond test (150 µm). Equation 3 shows how to obtain the Bond_{GP} value. This value is an average between the ratio of specific energy and the percentage passing 150 µm for the high and low energy tests.

$$Bond_{GP} = \frac{\left(\frac{Ecs_{High}}{\frac{P_{150\_H}}{100}} + \frac{Ecs_{Low}}{\frac{P_{150\_L}}{100}}\right)}{2} \tag{3}$$

Figure 6 shows the comparison between the Bond Ball Mill Test values performed and the Bond_{GP} parameter. Equation 4 shows a model to obtain the final Bond Ball Mill Geopyörä value, α and β are fitted parameters with values of 43.3 and 0.04 respectively.

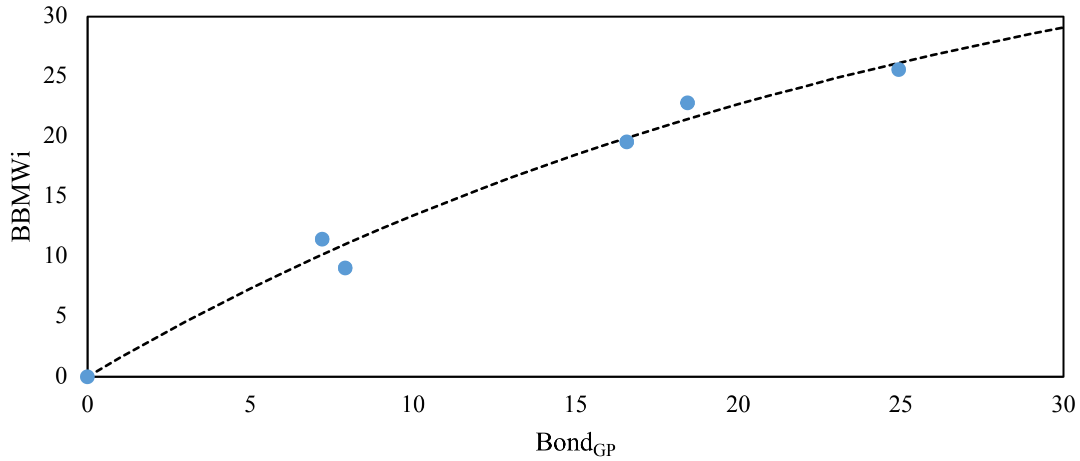

Fig. 6. Geopyörä BBMWi model

$$BBMWi = \alpha \cdot (1 - exp^{-\beta \cdot Bond_{GP}}) \tag{4}$$

Figure 7 shows a comparison between the BBMWi measured using the standard procedure and the BBWMi estimated using the Geopyörä data. A satisfactory correlation can be observed with four out of the five results within a relative error range of ± 20% (dashed lines), which is a sign that the Geopyörä can also provide a good estimation of ore hardness.

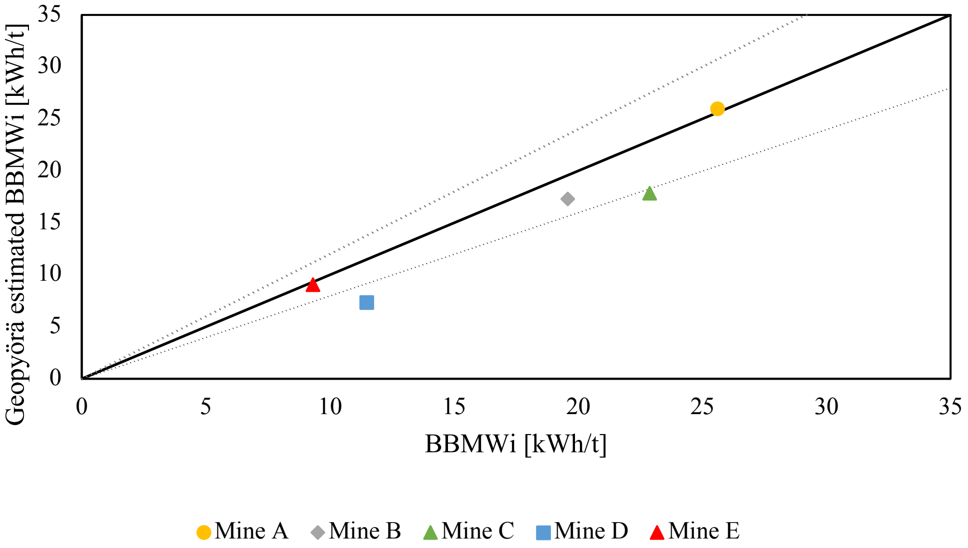

Fig. 7. Comparison of BBMWi and the Geopyörä estimated BBMWi

4. Conclusions

The Geopyörä was developed to be an ideal breakage test for both comminution and geometallurgy applications. It uses small discrete samples of less than a kilogram for bulk samples or halves of a one-meter long section of drill core. The test procedure is simple and fast, requiring approximately 20 minutes per sample, which ultimately results in a low-cost operation. Testing two sets of 15 particles at low and high energy levels has proved to be sufficient for estimating both ore competency (Axb) and hardness (BBMWi) parameters with acceptable accuracy.

The prototype tests were validated by comparing the results with industry-standard tests, such as the Bond ball mill test, the JK drop weight test and the SMC Test®. The correlation between the t_{10} measured using the standard JKDWT and the Geopyörä shows that both devices are generating equivalent results. Thus, the JKDWT Axb and SMC DWi parameters correlate appropriately with the results of the Geopyörä test, within a relative error of ± 20% across all samples. The estimation of BBMWi was considered adequate for comminution and geometallurgical modelling purposes. Nevertheless, future models with a larger database can undoubtedly increase the estimate accuracy.

The results obtained with Geopyörä were in good agreement to the current standard tests, which places the new testing device and method as a feasible option to test a large number of samples at low-cost and increase the understanding of ore variability from the comminution perspective. The proposed methodology is robust and suitable to be used with both drill cores in exploration or feasibility phases, as well as bulk samples to characterize breakage properties at industrial applications for throughput forecast.

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