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Comparative Analysis of Autogenous and Media Assisted Grindability of a Copper and Manganese Ores

E. O. Ajaka[1*], G. Dombo[2] and O. Abiodun[1]

[1]Department of Mining Engineering, School of Engineering and Engineering Technology, Federal University of Technology, Akure, Nigeria.
[2]Department of Mining and Metallurgical Engineering, Faculty of Engineering and Information Technology, University of Namibia, Ongwediva, Namibia.

Authors' contributions

This work was carried out in collaboration between all authors. Author EOA designed the study, jointly carried out the literature searches and laboratory tests with other authors, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Author GD sourced the ores and jointly performed the laboratory tests. Author OA managed laboratory equipment and report processing. All authors read and approved the final manuscript.

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ABSTRACT

This paper presents a comparative analysis of autogenous and media assisted grinding of a manganese ore and copper ore both obtained from Otjihase in Namibia. The objective was to understand the relationship between ore properties and Grindability and thus effectively select comminution circuit and equipment based on this relationship. Laboratory studies were carried out to determine the ease of grinding the ore samples relative to one another. The sample of known weight was crushed and the particles thoroughly homogenized for sieve size analysis and Grindability tests. The Grindability test on each ore was both autogenous and media assisted for dry grinding at -250 microns with constant mill charge of 200 g per run, media charge of 40% by weight and mill operations of 100 to 500 revolutions corresponding to mill speeds of 5 to 25 rpm.

**Corresponding author: Email: eoajaka@futa.edu.ng, akdenezezer@gmail.com;*

The Grindability index of each ore was calculated and compared based on the tests results and used to calculate work indexes for the ores based on the Bond's model. The autogenous tests produced average Grindability values of 0.55 kg/ton/rev and 0.65 kg/ton/rev for the copper and manganese ores respectively; and media assisted tests gave average values of 0.8 kg/ton/rev and 1.45 kg/ton/rev respectively for the copper and manganese ores. The results show that although media charge grinding produced higher Grindability values, both ores are economically amenable to autogenous grinding which suggests that with proper circuit design, the use of autogenous grinding for these ores (especially the manganese) can save significant cost. The results also show that Grindability increases with mill speed up to an optimum value beyond which grindability decreases with increasing speed and may even drop to zero while mill is running. It is also observed that grindability has close relationship with ore properties especially hardness and compressive strength. It should be noted that the inefficiency factors for the grinding are not considered in these results.

Keywords: Autogenous grindability; media assisted grindability; constant mass charge; addition of difference; inefficiency factor; optimum mill speed; pseudo-stationary.

1. GENERAL OVERVIEW

Run-off mines require a certain treatment before they are marketed as end products. The treatment may be simple size classification involving crushing and screening as in aggregates production or elaborate beneficiation involving physical cleaning and concentration of the ores. In nature, minerals of interest exist physically combined with the other (gangue) minerals of the host rock [1,2]. Removal of the unwanted gangues to increase the value (concentration) of the minerals of interest in an economically viable manner is the basis of mineral processing operations.

Ore beneficiation is commonly treated as combinations of unit operations. Each unit process and its stepwise operations are therefore treated separately. The greatest challenge to a mineral processor is to produce high grade concentrates consistently at maximum recovery from the ore and at the least possible cost [3,4,5]. To achieve this, a cost-effective comminution process that helps to liberate the minerals from the associated rock gangues must be carried out. Costly plants have been built to process minerals from host rocks over the years. The comminution units of such plants are known to carry the highest cost both at installation and production compared with the other unit operations of the plant. It is therefore essential that the method of comminution that will be most effective, yet least expensive for a particular ore be determined at the laboratory test stage, so that a cost-effective comminution circuit that will enhance total liberation of the values is selected at the design stage [3,6,7].

Crushing reduces the particle size of run-off-mine ore to such a level that grinding can be carried out until the mineral and gangues are substantially produced as separate particles [4,8,9]. Grinding in particular usually requires very high reduction ratio and thus always takes the largest portion of the entire comminution cost for some processing operations especially those requiring very fine grinding. Depending on the nature of rock materials with respect to strength, hardness, abrasiveness and other such properties, grinding may be assisted with the use of grinding media, carried out autogenously or semi-autogenously [5,7,8,10]. Grindability test is usually very essential in the selection of an effective comminution circuit [4,11].

Ore Grindability refers to the ease with which rock ores can be comminuted, and the data from Grindability test are used to evaluate crushing and grinding efficiency [12,13]. The most widely used parameter to measure ore Grindability is the Bond's work index [14,15]. Numerically, the work index is the energy required in kWh/short ton to reduce a given material from theoretically infinite size to 80% passing size of 100μm [14,16,17]. The determination of work index using modified Bond's method can be compared to method of determining it by [18] in 2006. This method requires the use of a reference ore of known Grindability [2,5]. Grindability usually increases with the fineness of grind, and it is based on performance efficiency in a carefully defined piece of equipment according to a strict procedure [5,7,10]. Using a refence ore is like comparing the Grindability values of two rocks of different strength properties and characteristics.

The main objective of this article, therefore, is to carry out both autogenous and media assisted Grindability tests on a manganese ore and copper ore both obtained from Otjihase area in Namibia; and compare their Grindability values relative to their strength parameters such as uniaxial compressive strength (UCS), hardness and abrasiveness values. This will help to determine how comminution energy vary with these properties and develop models for predicting energy based on these parameters. Although there are several models based on some complex mathematical theories that are used in recent times with computer applications to simulate comminution process, the Bond's work index model was used in this project. The results provide useful data on the relative Grindability of the two ores which will ease the process of selecting comminution equipment and circuits for their processing operations.

1.1 Grindability

Grindability is an important physical property of an ore that refer to the ease with which the ore ill perform in comminution in relation to energy and time [4]. It is very important to determine the hardness and grinding characteristics of an ore so that suitable crushing and grinding equipment of adequate size with require power can be selected for its comminution. This determines to a great extent among other things, the crusher selection, crushing circuit configuration and crushed ore size distribution; but most importantly, the grinding circuit type, equipment and control. It has been estimated that over 50% of the energy used in ore processing is consumed at the comminution stage [1,14].

The most widely used parameter to measure ore Grindability is the Bond's Work Index w_i. If the breakage characteristics of a material remain constant overall size ranges, then the calculated work index would be expected to remain constant since it expresses the characteristic resistance of the material to breakage [4,5]. The Bond standard Grindability test has been described in detail in literature. The procedure for determining Grindability as proposed by Bond is time-consuming, and a number of methods have been used to obtain the indices related to the Bond work index. [19] indicated that used batch-type Grindability tests to arrive at the work index, and compared their results with work indices from the standard Bond tests, which require constant screening-out of undersize material to simulate closed-circuit operation. The batch-type tests compared very favourably with the standard Grindability test data, the advantage being that less time is required to determine the work index.

2. MATERIALS AND METHODS

2.1 Materials

Manganese ore and Copper ore (chalcopyrite) were used in this work. These rock samples were collected from mining sites in Namibia. Texturally, both ores are fine-grained and the lumps appeared compact and massive with no visible cleavage. The manganese ore is dark grey and contains oxides of iron and manganese as major minerals with over 50% manganese oxides (MnO and Mn_2O_3) and about 20% iron oxide as hematite (Fe_2O_3). Magnesium oxide (MgO), silica (SiO_2), and calcium oxide (CaO) are also present at over 10%, 7% and 3% respectively. The copper ore is described as predominantly chalcopyrite ($CuFeS_2$) with a small amount of other copper minerals and free pyrite; traces of sphalerite and galena. The ore has lustrous dull-yellow appearance and, although no sign of cleavage is seen on physical examination, the ore appeared stained with some micaceous minerals.

Other materials, tools and equipment used were chosen according to the test requirements and some of these are a laboratory jaw crusher, a planetary ball mill, sieve shaker with set of sieves, digital weighing balance and others. The ball mill is a small digital laboratory-size mill with speed and time regulators which allowed for different experimental settings.

2.2 Preparation of Feed Materials

The ore lumps were broken to the average size of about 50 mm as feed to the jaw crusher. The broken ore samples were then crushed with the crusher set at 5 mm and the sieve size analysis carried out. The samples were then divided by quartering to ensure thorough mixes of batches after removing all size ranges below 250 micron - the size at which the Grindability tests were conducted.

2.3 Methods

Full autogenous and media-assisted Grindability techniques were employed to compare the ease of grinding of the selected rocks. Both tests were carried out at -250 microns (-250µ) using constant mass charge by addition of difference and new mass charge procedures. Autogenous grinding tests were carried out without any grinding media addition, while media-assisted tests were carried out with 45% media (ball) charge. A constant mass of 200 g was used in all grinding tests. The choice of this value was based on the volume of the mill grinding chamber with consideration for media charge and allowable total charge volume of the mill.

Each measured batch of 200 g material was ground for 20 minutes at 100, 200, 300, 400 and 500 revolutions of the mill which corresponded to mill speeds of 5 rpm (revolutions per minute), 10 rpm, 15 rpm, 20 rpm and 25 rpm respectively, and the content of the mill was discharge and weighed after each run. The sieve size analysis of the product was carried out and the weight of material less than 250 microns is taken.

In the constant mass charge by addition of difference, the -250µ fraction of the product was removed and new feed equivalent to its weight added for another test run. But in the new mass charge, 200 g of fresh feed was measured after each test and used in another run.

Each grindability value was expressed in kilograms per tons per revolution (kg/ton/rev) and Bond's model (Equation 2) used to determine a Grindability index value. Three runs were made for each batch of test, and the average value recorded.

$$G_r = \frac{Weight\ (W_{-250})}{Number\ of\ revolutions} \tag{1}$$

Bond work index (BWI - w_i) was determined using the expression in Equation 2 [20].

$$W_i = \frac{48.95}{D^{0.23} G^{0.82}\, 10\left[\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right]} \tag{2}$$

Where

F_{80} – Feed size (microns) through which 80% of the feed passed
P_{80} – Product size (microns) through which 80% of the feed passed
D – Aperture (microns) of the classifying screen
G – Net weight of (grams) of undersize (-250 microns) product per unit revolution of the mill,
w_i – Bond work index in kWh/t

It should be noted that the type of grindability tests carried out is not the conventional test of grinding to constant product weight to impose a circulating load on the system, rather, it is a grinding test conducted to determine the ease of grinding the ores under different condition and the effects of variation of some other parameters like the mill speed and type of grinding on grindability value. Thus, grindability as used here is the amount of material finer that the test size (-250 microns) produced per revolution of the mill.

2.4 Sieve Analysis Test

Sieve size analysis of the crushed product was carried out with 10 pieces of sieves from 63microns to 5000microns and the size which 80% passed through determined from the sieve analysis plots.

3. RESULTS AND DISCUSSION

Results of the work carried out are illustrated in Tables 1 – 7 and Figs. 1- 10. The two test modes (addition of difference and new mass charge) used in this work have different implications in plant application. The addition of difference mode is applicable in continuous grinding operation while the new mass charge is intended for use in batch grinding. Although the tests were carried out at 250 microns, the results can be applied to grinding to finer sizes, especially in regrind mills for recovery by flotation.

Tables 1 and 2 present the grinding test results as measured, while Tables 3 – 6 present the Grindability values calculated with Equation 1 using the measured results. Tables 5 and 6 especially present the results in grams per tonne per revolution (g/ton/rev) for easy application in plant comminution analysis. This is also easily expressed in kilogram per tonne per revolution (kg/ton/rev).

Although the volume of the grinding chamber of the laboratory mill used in this test is small and the mill chamber inside diameter is 0.15m, the results can be used in a scaled-up design by applying the mill diameter inefficiency correction

Table 1. Average grindability results for the copper ore (grams)

Mill Speed (rpm)	Media-Assisted (MA) (g)		Autogenous (AG) (g)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	0	0	0	0
10	48	61	19	15.5
15	105.5	119.5	40.5	30.5
20	148	162	55	41
25	174.5	182.5	64.5	58

Table 2. Average grindability results for the copper ore (grams/rev)

Mill Speed (rpm)	Media-Assisted (MA) (g/rev)		Autogenous (AG) (g/rev)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	0	0	0	0
10	0.24	0.305	0.095	0.078
15	0.352	0.398	0.135	0.102
20	0.37	0.405	0.138	0.103
25	0.349	0.365	0.129	0.116

Table 3. Average grindability results for the copper ore (grams/ton/rev)

Mill Speed (rpm)	Media-Assisted (MA) (g/ton/rev)		Autogenous (AG) (g/ton/rev)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	0	0	0	0
10	1200	1525	475	390
15	1760	1990	675	510
20	1850	2025	690	515
25	1745	1825	645	580

Table 4. Average grindability results for the manganese ore (grams)

Mill Speed (rpm)	Media-Assisted (MA) (g/rev)		Autogenous (AG) (g/rev)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	0.5	0	0.3	0
10	24	35	18	10
15	68.5	92.5	37.8	29.7
20	102	128.5	48.5	41.5
25	142.5	160	63.8	50.5

factor (Equation 3) as suggested by [21] to correct the inadequacy of mill size.

$$F_d = \left(\frac{2.44}{D}\right)^{0.2} \tag{3}$$

The polynomial trendlines of the plots of grindability with mill speed which gave the best fits of the results of experimental runs (with only minor adjustments of few obvious errors in measurement) are presented in Figs. 1 to 10.

As expressed in Equation 1, the grindability of a material is affected by the mill speed. The equation shows grindability value as dependent on the number of mill revolution which in turn

Table 5. Average grindability results for the manganese ore (grams/rev)

Mill Speed (rpm)	Media-Assisted (MA) (g/rev)		Autogenous (AG) (g/rev)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	0.005	0	0.003	0
10	0.12	0.175	0.09	0.05
15	0.228	0.308	0.126	0.099
20	0.255	0.321	0.121	0.104
25	0.285	0.32	0.128	0.101

Table 6. Average grindability results for the manganese ore (grams/ton/rev)

Mill Speed (rpm)	Media-Assisted (MA) (g/ton/rev)		Autogenous (AG) (g/ton/rev)	
	Addition of Difference	New charge	Addition of Difference	New charge
5	25	0	15	0
10	600	875	450	250
15	1140	1540	630	495
20	1275	1605	605	520
25	1425	1600	640	505

depends on how fast or slow the mill is driven. Since different mill speeds were used in this work, the optimum mill speed for each test type and mode was used to calculate average work indexes for the tests using Equation 2. Observing from Figs.1 to 10, Grindability values increased sharply with increasing mill speed until it started to decrease after about 20rpm. This trend was the same for all test types and modes. Obviously, the optimum mill speed for all the tests (based on the trendline equations) can be taken as 20 rpm. Although some values were as high as 24 rpm, the majority of the peak values are about 20 rpm. Thus, the grindability values (in grams per revolution) that correspond to this mill speed are used to calculate work indexes for the ores according to the type and mode of experimental tests.

Although the maximum mill speeds for the different tests in this investigation differ slightly, 20rpm was used as optimum mill speed for all tests. This is because the more the goodness of fit [R^2] of the plots of trend data approaches unity (1), the closer the mill speed trends toward 20rpm. This is confirmed by differentiating the trendline equations with respect to the mill speed (n) and determining the algebraic turning point at which grindability value is expected to be zero. For example, Equations 4 and 5 are the trendline equations for autogenous grinding in the new charge and addition of difference modes for the copper ore (Fig. 1). Differentiating the equations and solving for n, (the mill speed) at the turning point gave n = 19.30 for and 20.88 for new charge and addition of difference respectively. The rest of the curves follow the same trend – approaching 20rpm with increasing goodness of fit.

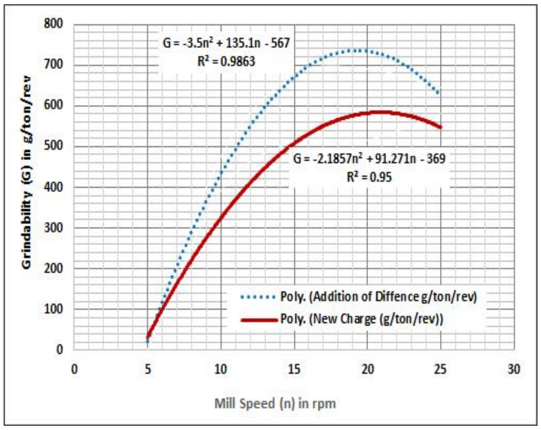

Fig. 1. Autogenous Grindability for copper ore for both test modes

$$G = -3.5n^2 + 135.1n - 567 \quad (4)$$

$$G = -2.1857n^2 + 91.271n - 369 \quad (5)$$

$$For\ Equation\ 4, \quad \frac{dG}{dn} = -7n + 135.1$$

At maximum point, $\frac{dG}{dn} = 0$, i.e. n = 19.30 Similarly,

$$\frac{dG}{dn} \; for\ Equation\ 5\ is \; -4.3714n + 91.271$$

i.e. n = 20.88

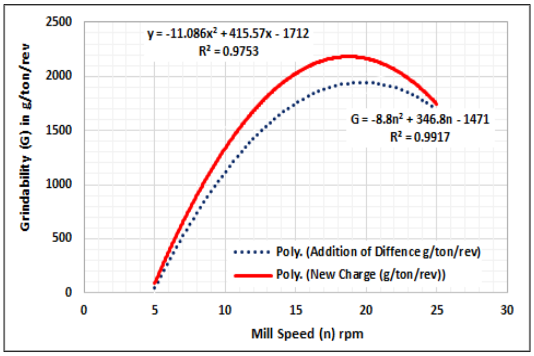

Fig. 2. Media assisted Grindability for copper ore for both test modes

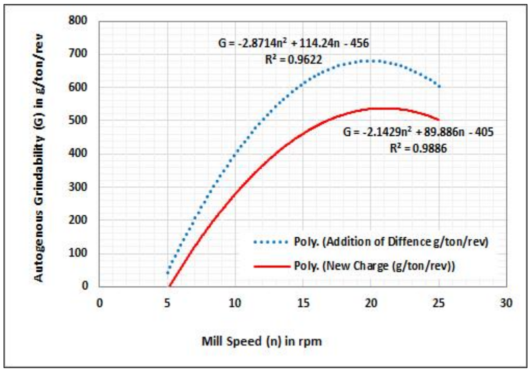

Fig. 3. Autogenous Grindability for manganese for both test modes

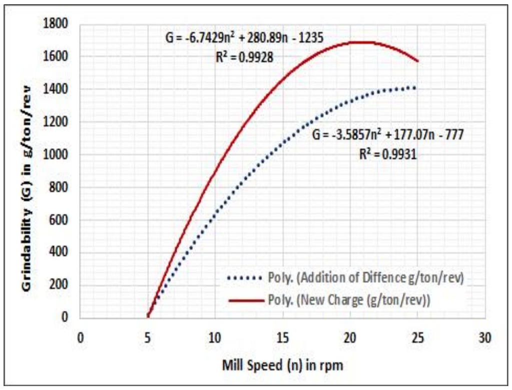

Fig. 4. Media Assisted Grindability for manganese for both test modes

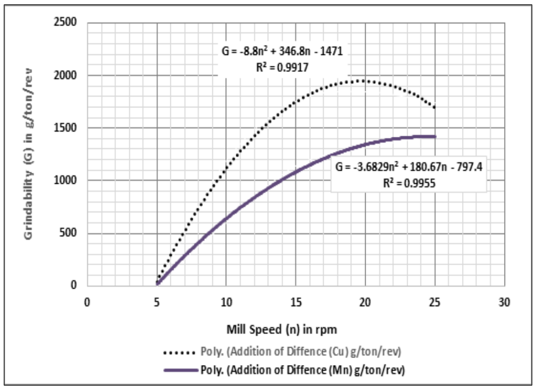

Fig. 5. Media assisted Grindability by addition of difference compared for the copper and manganese ores

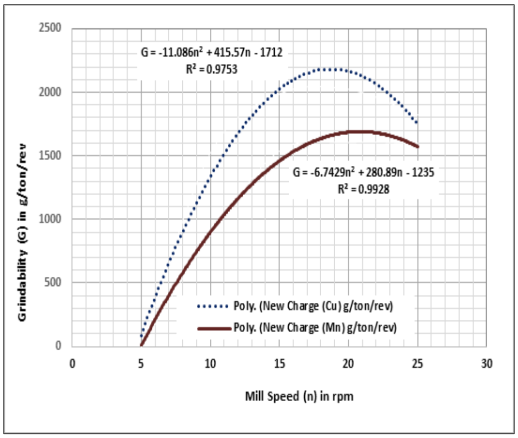

Fig. 6. Media Assisted Grindability by new charge compared for the copper and manganese ores

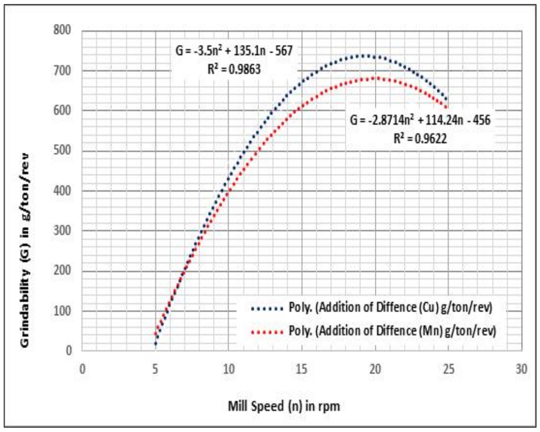

Fig. 7. Autogenous Grindability by addition of difference compared for the copper and manganese ores

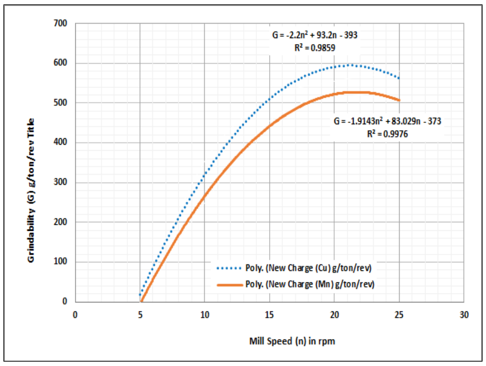

Fig. 8. Autogenous Grindability by new charge compared for the copper and manganese ores

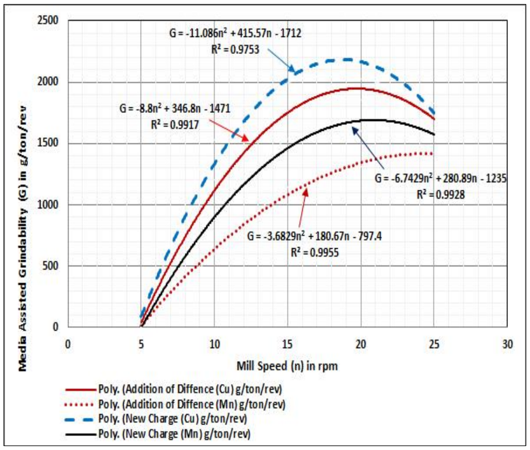

Fig. 9. Media assisted Grindability for manganese and copper ores in new charge and addition of difference modes compared

From particle size analysis of initial feed (Figs. 11 and 12), the sizes which 80% of the feed passed through are 3950 microns and 2800 microns for manganese and copper ores respectively (Table 7). This size [F_{80}] is taken as the same for all runs and used in calculating hypothetical Bonds work indexes for both Ores in all modes. The product size F_{80} which 80% of the products passed through was estimated from the different particle size analyses of the different tests. The grindability values produced by the different grinding modes are very close, such that an average value can be used to determine a rough work index for each ore. The Grindability values produced by each test type and mode were therefore calculated at the optimum mill speed of 20 rpm (Table 7) using the trendline equations and used to determine average Grindability for work index calculation.

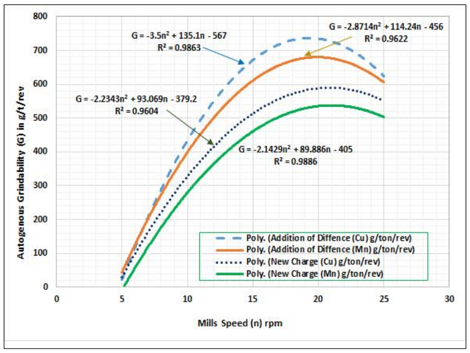

Fig. 10. Autogenous Grindability for manganese and copper ores in new charge and addition of difference modes compared

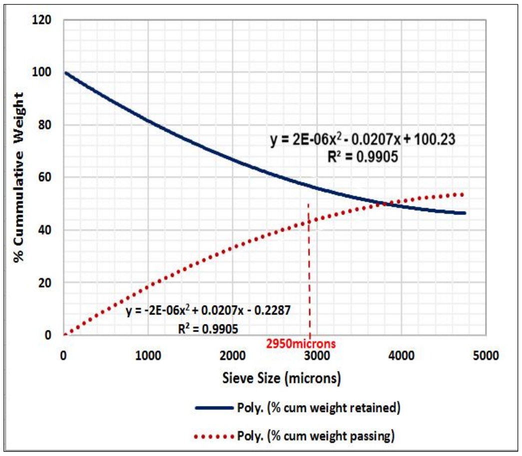

Fig. 11. Particle size analysis of product for Grindability test for manganese ores

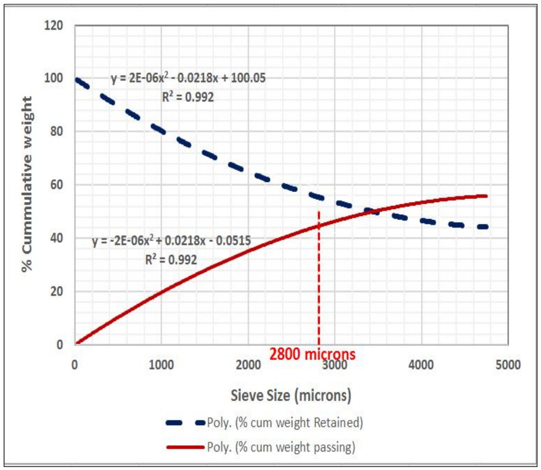

Fig. 12. Particle size analysis of product for Grindability test for copper ores

Table 7. Feed/product passing sizes for Grindability tests

Ore type	Test mode	80 % Size P_{80} (microns)		Grindability at 20rpm (g/rev)	
		AG	MA	AG	MA
Cu	Addition of Difference	2100	1850	0.147	0.389
(F_{80} = 2800)	New Charge	2100	1850	0.117	0.438
	Average			0.132	0.411
Mn	Addition of Difference	2250	2050	0.136	0.470
(F_{80} = 2950)	New Charge	2250	2050	0.107	0.266
	Average			0.122	0.368

Using Equation 2, the work indexes for the different test modes for each ore at maximum mill speed were calculated. The mill size was also corrected using Equation 3 with the mill diameter of 10 cm (0.1m). The results are shown in Table 8.

Table 8. Calculated work indexes for the different tests modes

Ore type and test mode	Work Index (w_i) (kWh/t)	
	AG	MA
Copper ore (as-milled)	7.29	16.13
Copper ore (corrected for mill Size)	13.82	30.55
Manganese ore (as-milled)	7.49	18.08
Manganese ore (corrected for mill size)	14.19	34.24

It should be noted that the calculated work indexes shown in this table are only a rough estimate since the procedure for obtaining the grindability values is designed for simple grinding test

In a test carried out for another research, the uniaxial compressive strengths (UCS) of the two ores were determined as 68MPa and 60MPa for the manganese and copper ores respectively. Thus, it is obvious that the manganese ore is stronger and (all other factors being constant) will give more resistance to breakage (comminution) than the copper ore. As a result, the grindability values for all test types and modes are higher for the copper ore than for the manganese ore as shown in Figs. 9 and 10. Therefore, in applying the results of these tests to the design of comminution circuits for the concentration of these ores, it is important to remember that the manganese ore will require more energy both in crushing and grinding than the copper ore. The number of crushing stages may be the same for both ores but energy consumption will definitely be different. However, if the difference in energy consumption will exceed 20%, it is reasonable to introduce another crushing stage in the circuit for the manganese ore.

The energy required can be calculated from Bond’s model and compared for the two ores. The result also indicated that autogenous grinding is applicable to both ores, but in all grinding applications, the necessary inefficiency correction factors must be applied. As stated earlier, the diameter inefficiency factor (Equation 3) is applicable to the results of both ores for all the test types and modes undertaken in this research. For most real plant operations, grinding is carried out wet, but all tests in this research were carried out dry; and according to Chester, (2003), dry grinding requires about 1.3 times more energy than wet grinding. Thus, dry grinding inefficiency factor (F_g) must also be applied to the calculated Bond’s energy. The required total energy will, therefore, be given by Equation 4. If either of the ores will be concentrated by flotation, then grinding will be done to size finer than the 250 microns used in this work.

$$\begin{aligned} W_T &= W_{cr} + W_{Gr} \\ &= W_{cr} + F_d F_g\ W_{crR} \\ &= 10\ W_i\ [P_c^{-0.5} - F_c^{-0.5}] + 10\ W_i\ [P_g^{-0.5} - F_g^{-0.5}]\ F_d F_g \end{aligned} \qquad (4)$$

Where,

W_{cr} - Energy for crushing,
W_{Gr} - Energy for grinding,
F_d - Mill Diameter Inefficiency Factor,
F_g -Dry Grinding Inefficiency Factor,
W_i - Work index
P_c - 80% passing product size for crushing
P_g - 80% passing product size for grinding
F_c - 80% passing feed size for crushing
F_g - 80% passing feed size for Grinding

It is also observed from the results that for autogenous tests, grindability values are higher for addition of difference mode than in new charge mode. But in the media assisted tests, the values are higher for new charge mode than for addition of difference mode (Figs. 1- 4). Although grindability values are expectedly higher in media assisted runs than in autogenous, the swap for maximum values between addition of difference and media assisted in the two test modes may be due to a number of factors which are likely to include feed properties in addition to the mechanism of breakage.

The crushed materials used as feed had irregular edges with grains that were weaker than internal grains. These peripheral grains (already weakened by crushing impact) are easily removed by any further impact, even little interaction between particles as a result of attrition in grinding. As the peripheral grains are removed by successive grinding impact, the particles gradually attained pebble or spherical shape with smooth edges; so, it takes greater impact to remove more grains from the edges which simply translate to more resident time in the mill. It should be noted that a particle will break into a number of smaller particles, but as grinding progresses, each particle gradually approaches spherical shape. Thus, for media assisted grinding in new charge mode, maximum quantity of grains would be removed from the particles since a completely new weight of 200 g of material is charged into the mill for each run, whereas in the addition of difference mode, only the small quantity of +250 microns material added after each run have such edges with weak grains and the amount of new grains removed from the charge will be very small compared to the new charge mode, thus reducing grindability. Of course, a given particle will also split into many smaller particles and thus present fresh edges from which grains will be further removed, but this phenomenon is common to all modes and the effect will therefore be similar.

The results also indicate that there is a speed limit for optimum performance of the mill. From the results, we can reasonably conclude that when mills are driven too slowly, they are under-utilized and thus reduces the plant capacity. In similar manner, when mills are driven too fast, they under-produce and yet consume more energy thereby increasing cost. With careful test, however, a speed limit can be determined which gives optimum performance; and beyond this speed, grindability begins to decrease as shown in this work where the optimum mill speed is about 20rpm based on the grinding equipment used.

Figs. 1-10 show that the reduction in grindability values with increasing mill speed may be sharper beyond the optimum speed than prior to it. This observation is drawn from the fact that most of the plots appeared to be a little skewed to left of the maximum speed, implying that at speed far higher than the optimum, grindability may drop drastically to a limiting value even to zero. The most likely reason for this observed trend is that as mill speed increases, the centrifugal force on mill content (charged material) also increases; and at a particular speed, the mill content tends to attain the same speed as the mill chamber and then become somehow pseudo-stationary rather than interacting. This is thought to be a possibility since most mills (especially the one used in this research) are tumbling mills. For example, following the trend equations, the mill speed becomes too high for both copper and manganese ores in autogenous mode for addition of difference that the grindability values dropped to zero at 35rpm faster than it increased with mill speed as shown in Fig. 13. The same is observed for media assisted mode in Fig. 14. Although it appears as if the quadratic relation is symmetrical, a little skewness to the left can be seen. This implies that at a particular mill speed (above maximum speed), no grinding was actually taking place because all mill contents have attained the same angular speed as the mill itself and so have zero relative motion to one another and to the mill chamber, although the mill is in motion.

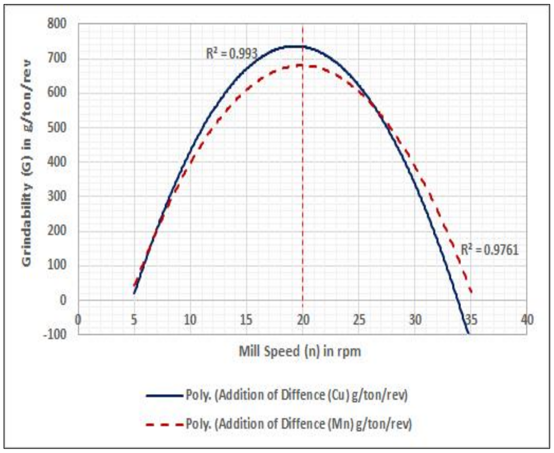

Fig. 13. Symmetrical relationship of Grindability with mill speed for autogenous

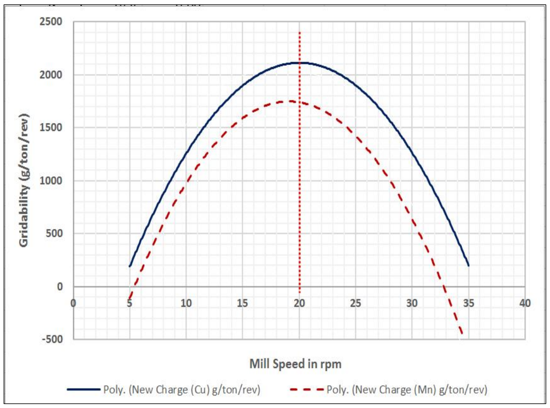

Fig. 14. Symmetrical/skewed relationship of Grindability with mill speed for media assisted

4. CONCLUSION

Grindability values obviously vary according to rock type. The average grindability values of manganese for both autogenous and media assisted tests at various mill speeds are lower than those for the copper ore for the two test modes, implying that the copper ore can be comminuted much easier than the manganese ore. How quickly an ore can be ground also depends on ore hardness, percent media charge, optimum mill charged volume, and most important on the mill speed (up to a limiting value) beyond which grindability decreases with increasing speed. Although the mill used in this test is a small laboratory mill, the results will apply well to larger mills once the necessary inefficiency factors have been applied for correction of certain conditions and aspect ratios.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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