Songklanakarin J. Sci. Technol.
41 (3), 664-668, May - Jun. 2019

http://www.sjst.psu.ac.th

Original Article

Hardgrove grindability index and approximate work index of sodium feldspar

Chairoj Rattanakawin[1*] and Aung Lay Tin[2]

[1] *Department of Mining and Petroleum Engineering, Faculty of Engineering, Chiang Mai University, Mueang, Chiang Mai, 50200 Thailand*

[2] *Department of Mining Engineering, Yangon Technological University, Yangon, 11012 Myanmar*

Received: 29 June 2017; Revised: 30 August 2017; Accepted: 17 February 2018

Abstract

The purpose of this research was to study the feldspar of Nopphitam District, Nakhon Si Thammarat Province, Thailand with emphasis on Hardgrove grindability and determination of the approximate work index. Feldspar samples were collected, prepared, and analyzed for their chemical composition. From the analysis of the alkaline metal oxides, all samples were characterized as sodium feldspar. The Hardgrove grindability test used a ball-race test mill. The Hardgrove grindability indices of these feldspar samples had an average of 46.25. Knowing the average Hardgrove index, a calculated work index of 12.88 kW/STPH was estimated using Aplan's empirical formula. This average work index was less comparable to those of feldspar ores given in the literature. Therefore, the method of Berry and Bruce was used to determine the specific energy and approximate work index. By running a batch dry-grinding test in a rod mill, an average specific energy of 7.34 kW/STPH was determined using Bond's formula with the reference work index of 11.25 kW/STPH. This specific value is limited to these test conditions: (1) 18x36 cm mill with material hold-up of about 0.08, media loading of about 0.4, and half interstitial filling and (2) each sample must be ground by 8 steel rods with dimensions of 3.5x35 cm each for 15 min. Under these conditions, the approximate work indices of various minerals can be rapidly estimated knowing the 80% passing size (μm) of both feed and product from rod-milling that conforms to the indicated conditions. For example, the approximate work index of Sam Ngao sodium feldspar was 11.03 kW/STPH. This work index was quite comparable to those acquired from various mill manufactures. To obtain more accurate values of sodium feldspar's work indices, the time-consuming Bond procedure should be performed with a number of corrections for different milling conditions.

Keywords: approximate work index, Hardgrove grindability index, sodium feldspar

1. Introduction

Comminution is an operation whereby mineral particles are size-reduced by crushing and grinding to product sizes required for further processing or end use. About 50% of a mineral processing plant's operating costs are consumed as energy in size reduction (Herbst, Yi, & Flintoff, 2003). These operations are not only energy intensive, but also energy inefficient. For example, the approximate energy efficiency of a rod mill is only about 7%. Therefore, the grindability of a mineral ore with the appropriate mill is very important. It can be used to measure comminution characteristics and to evaluate grinding efficiency leading to reducing of the processing cost in the mineral industry.

A study of grindability is to evaluate the size and type of mill needed to produce a specified tonnage and power requirement for grinding. The specific energy - mill power over-capacity - is a main parameter for mill sizing. If an

*Corresponding author
Email address: chairoj@eng.cmu.ac.th

empirical law of comminution is assumed, then the grinding behavior can be expressed as an energy coefficient or work index. Specifically, the Bond work index is suitable for utilization in many industrial grinding processes with particle sizes ranging from 1 mm to 1 μm (Rhodes, 1998).

Bond defined the work index (W_i) as the work (kWh per short ton) used to reduce particles from theoretically infinite size to 80% passing 100 μm. Bond's formula is derived from an empirical differential equation of grinding energy with the exponent of 1.5 as followed:

$$E_B = 10W_i\,(1/X_{p,80}^{0.5} - 1/X_{f,80}^{0.5}) \quad (1)$$

where E_B is the specific energy (kWh/st or kW/STPH), $X_{p,80}$ is the 80% passing size (μm) of a product, and $X_{f,80}$ is the 80% passing size (μm) of a feed. The 80% passing sizes of both product and feed are normally obtained from the Gaudin-Schuhmann plot. The size distribution in this plot can be expressed as the mass distribution function of a simple power law (Hogg, 2003) as:

$$Q_3(x) = (x/k_s)^{\alpha} \text{ if } x \leq k_s \text{ and } Q_3(x) = 1 \text{ if } x \geq k_s \quad (2)$$

where $Q_3(x)$ is the mass cumulative % finer than size x, k_s is the size modulus and α is the distribution modulus. On the other hand, the 80% passing sizes can be obtained from the size distribution function if the size modulus and distribution modulus of the specific size and grinding condition are known.

Bond (1961) and Bond (1963) described a standard procedure to determine work index at length. Pongprasert *et al.* (1994) followed the procedure step by step using a lab ball mill to determine the Bond work index of feldspar ore from Nopphitam District, Thasala, Nakhon Si Thammarat, Thailand. However, this procedure, when performed in a steady state condition with an equilibrium circulating load in a locked cycle test, is time-consuming. Berry and Bruce (1966) developed a comparative method to determine the grindability of an ore. By knowing a specific energy for the grinding of a reference ore, the work index of an unknown ore can be determined from Bond's equation with the identical energy.

The Hardgrove test is a standard method used widely in the coal industry. To determine the relative grindability of coal, i.e. whether it is easy or difficult to pulverize, the Hardgrove grindability index (HGI) can be estimated from the test. A higher index indicates the coal is easier to pulverize. This is opposite to the pattern found with the Bond work index where soft mineral ores generally have low work indices. Aplan, Austin, Bonner, and Bhatia (1974) and Aplan (1996) have shown a correlation between HGI and W_i in U.S. coal though these two indices are based on quite difference test procedures. The approximate relationship is based on this equation:

$$W_i = 511/(\text{HGI})^{0.96} \quad (3)$$

It should be noted that this empirical formula may be used to estimate the W_i given the HGI or vice versa. This formula has been found to hold for coal samples with a wide variation in HGI as well as for several ore samples.

The purpose of this research was to do tests on the grindability of Nopphitam feldspar with emphasis on the HGI and the determination of the approximate W_i. Once the W_i and E_B of this reference feldspar is known, the approximate work index of an unknown feldspar can be rapidly estimated from rod-milling that conforms to the indicating conditions.

2. Methodology

Chemical analyses of Nopphitam reference feldspar samples were performed. The HGI of each sample was then determined from the Hardgrove grindability test. Then an approximate W_i of each sample was calculated from the corresponding HGI value using Aplan's formula. Meanwhile the E_B of each sample was evaluated from rod-milling with the specific work index and conditions. Finally, the approximate W_i of an unknown Sam Ngao feldspar was estimated from Bond's formula with the average E_B, $X_{p,80}$ and $X_{f,80}$ of the rod-milling grindability test.

2.1 Chemical analyses

Nopphitam feldspar samples were collected from various mining sites at Thasala, Nakhon Si Thammarat in southern Thailand. These samples are the representatives of feldspar ores previously studied by Pongprasert *et al.* (1994) in the topic of Bond grindability work index determination. There were four reference samples coded as BY1, BY2A, BY-2B, and PG2A. And one unknown feldspar sample named as FWC was collected from Sam Ngao, Tak Province in northern Thailand. All samples were analyzed by the Department of Primary Industries and Mines (DPIM), Regional Office 3, Chiang Mai, Thailand.

2.2 Hardgrove grindability test

Hardgrove grindability test was performed by the Geology Department, Mae Moh Mine Planning and Administration Division, Electricity Generating Authority of Thailand. The reference feldspar samples were pulverized according to the procedure described in the ASTM D-409-02 standard test method (American Society for Testing and Materials [ASTM], 1993) for grindability of coal by a ball-race Hardgrove mill. This standard procedure carried out by Rattanakawin and Tara (2012) was described elsewhere.

2.3 Rod-milling grindability test

From the method of Berry and Bruce, the specific energy may be determined by running a batch dry-grinding test. The test was performed using an 18x36 cm rod mill with material hold-up of about 0.08, media loading of about 0.4 and half interstitial filling. Each reference sample was ground by 8 steel rods for 15 min. Each rod had the dimensions of 3.5x35 cm. After that, the feed and product from the rod-milling were sieved using U.S. mesh series. Then the particle size distributions were plotted on log-log paper. Knowing the $X_{f,80}$ and $X_{p,80}$ from this Gaudin-Schuhmann plot or those values from Equation 2 together with the W_i of reference samples from Pongprasert *et al.* (1994), the E_B of this rod-milling grindability test was estimated from Equation 1. Conversely, an approximate W_i of an unknown sample was determined knowing the averaged E_B from this grindability test, $X_{f,80}$ and $X_{p,80}$.

3. Results and Discussion

3.1 Chemical composition of reference and unknown samples

The chemical composition of the reference and unknown feldspar samples are shown in Table 1. From the ratio of alkaline metal oxides considered, all samples could be characterized as sodium feldspar because the content of Na_2O was much higher than K_2O. This characterization was in accordance with the sodium feldspar samples from Thasala, Nakhon Si Thammarat by Department Primary Industries and Mines (DPIM, 2007) and from Nam Dip, Tak Province by Rattanakawin, Phuvichit, Nuntiya, and Tonthai, (2005). For example, the average content of Na_2O and K_2O in sodium feldspar from Sam Ngao, Tak Province was about 9% and 0.5% respectively

Table 1. Chemical composition of reference and unknown feldspar samples.

	Sample	BY1	BY2A	BY2B	PG2A	FWC
Chemical Composition	SiO_2	77.18	70.15	68.48	66.24	58.18
	Al_2O_3	13.19	16.75	19.68	19.60	17.25
	Fe_2O_3	0.29	0.29	0.40	0.24	4.49
	CaO	0.33	0.26	0.27	0.22	1.46
	MgO	0.27	0.10	0.20	0.05	3.56
	K_2O	0.46	0.41	0.52	1.72	0.18
	Na_2O	7.60	10.98	9.87	11.11	10.89
	LOI	0.50	0.39	0.46	0.24	3.74

3.2 Hardgrove grindability and calculated work indices

The HGI values of reference sodium feldspar samples are shown in Table 2. It is clear that the HGI values were virtually the same with an average of 46.25. As a result, the W_i calculated from these HGI values (Equation 3) of those corresponding samples were very similar at an average of 12. 88 kW/STPH. This averaged W_i was less comparable to that of the feldspar ore reported by Pongprasert *et al.* (1994) with the value of 11.25 kW/STPH. It is also different from those work indices given by various mill manufacturers such as Metso Minerals (2018), Doering International GmbH (2015), Cement and Mining Technology GmbH (CEMTEC, 2015), Allis Chalmers Corporation (1999), and Tenova Mining & Minerals (Pty) Ltd. (2015) with the values of 10.80, 10.88, 11.32, 11.67, and 11.79 kW/STPH respectively. It was evaluated that the accuracy of the averaged W_i value was less than 86% compared to the reported value from Pongprasert, *et al.* (1994) and those of the manufactures. Aplan's formula seems to be invalid for the sodium feldspar studied. This was possibly because the physical characteristics of feldspar are much different from coal, i.e. feldspar is a hard, brittle, and abrasive rock comparing to a lump of coal (NEDO, 2003) which is normally studied using a Hardgrove mill. Therefore, the reported value was used to calculate a specific energy of rod-milling grindability test using the approach of Berry and Bruce.

Table 2. HGI and calculated W_i from HGI of reference sodium feldspar samples.

Sample	HGI	Calculated W_i from HGI (kW/STPH)
BY1	46	12.95
BY2A	46	12.95
BY2B	47	12.68
PG2A	46	12.95
Average	46.25	12.88

3.3 Calculated specific energy and approximate work index

The calculated specific energy of the reference samples BY1, BY2A, BY2B, and PG2A were 7.28, 7.42, 7.55, and 7.13 kW/STPH, respectively (Table 3). These calculated values were obtained from the reported work index and the 80% passing sizes of both product and feed from the Gaudin-Schuhmann plots. For example, the reported W_i of the reference samples was 11.25 kW/STPH and the corresponding $X_{p,80}$ and $X_{f,80}$ from the rod-milling of BY2A that conformed to the indicated conditions were 151 and 4,200 μm (Figure 1). Then the specific energy calculated from Equation 1 equaled 7.42 kW/STPH.

Contrary to the specific energy estimation, the approximate work index of the unknown FWC sample was 11. 03 kW/STPH. This approximate value was calculated from Equation 1 knowing the average E_B of the reference samples of 7.34 kW/STPH ($X_{p,80}$=144 and $X_{f,80}$=3,549 μm) from the plot in Figure 2. Compared to the average work index acquired from the above-mentioned manufacturers, the approximate work index of Sam Ngao sodium feldspar was plausibly the same. The precision of this value was indeed about 98%. Furthermore this methodology can be applied to any hard, brittle, and abrasive rock, such as granite, quartz, and porphyry, by running a batch dry-grinding test of an unknown sample using the rod mill at the given conditions. If the work index of quartz vein gold ore from Chatree Gold Mine in Phichit Province is determined by this method to be about 12.75 kW/STPH and the ore is to be ground with the capacity of 340 STPH from infinite size to 75 μm in order to liberate gold particles for further cyanidation (Akara Mining Ltd., n/a), an approximate horse power to drive the mill would be 5,000 calculated using the Bond formula for example. From the calculated mill power, an appropriate mill can be selected and sized from the manufacturers' catalogs.

Table 3. Calculated E_B from the reported W_i.

Sample	Calculated E_B from reported W_i (kW/STPH)
BY1	7.28
BY2A	7.42
BY2B	7.55
PG2A	7.13
Average	7.34

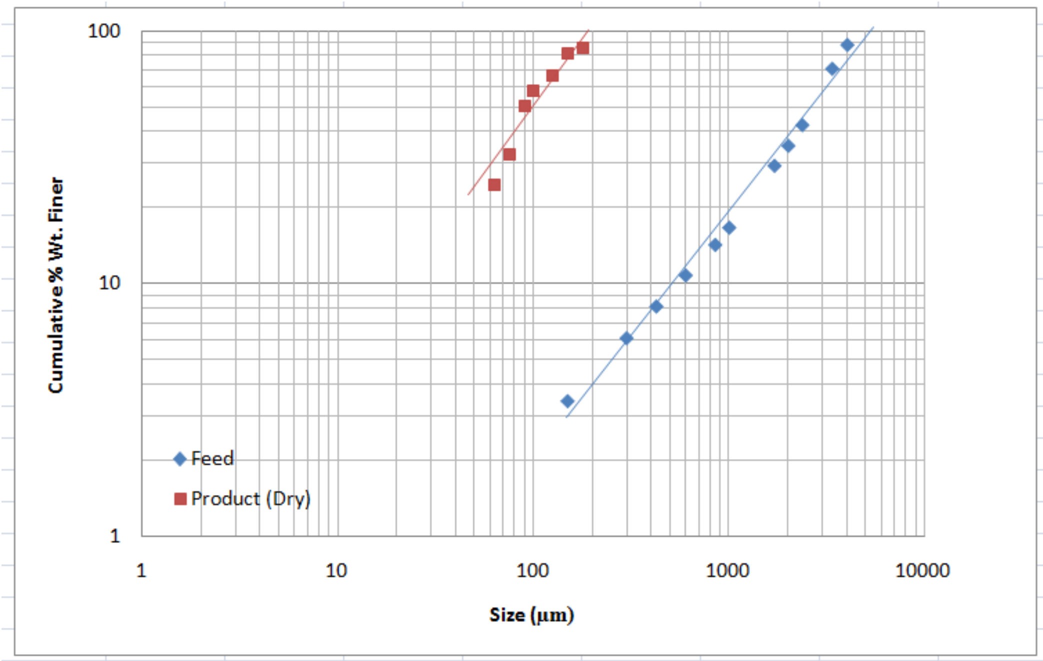

Figure 1. Size distributions of the reference BY2A feldspar feed and product samples on the Gaudin-Schuhmann plot.

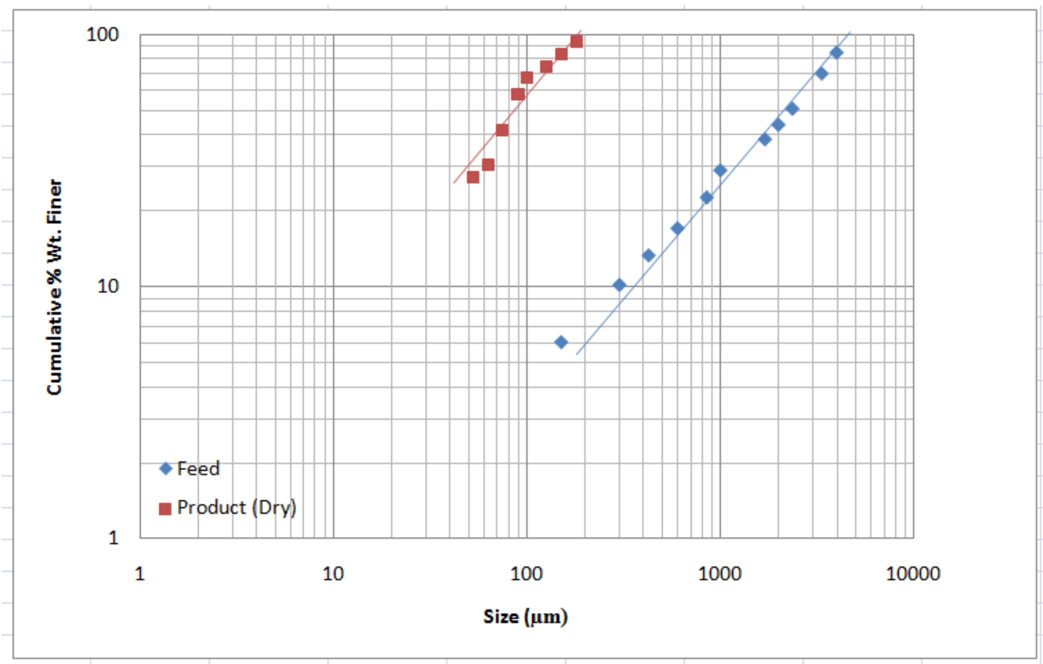

Figure 2. Size distributions of the unknown FWC feldspar feed and product samples on the Gaudin-Schuhmann plot.

4. Conclusions

From the ratio of alkaline metal oxides in chemical composition, all samples were characterized as sodium feldspar. The work index of the Nopphitam reference sodium feldspar that was calculated from the Hardgrove grindability indices was about 12.88 kW/STPH. The averaged work index was less comparable to that of feldspar ore reported by Pongprasert *et al.* (1994). Also, it was different from the averaged values given by various mill manufacturers. Aplan's formula seemed to be invalid for the sodium feldspar studied. Therefore, the reported value of 11.25 kW/STPH was used to calculate the specific energy of the rod-milling grindability test using the approach by Berry and Bruce. Furthermore, from the average specific energy of the reference samples (7.34 kW/STPH), an approximate work index of an unknown feldspar can be rapidly estimated when we know the 80% passing size of both feed and product from the grindability test that conforms to the indicated conditions. It was found that the work index of Sam Ngao sodium feldspar was 11.03 kW/ STPH. This value compares well with the average work index acquired from the manufactures. It is suggested that the time-consuming Bond procedure be employed with a number of corrections for different milling conditions to obtain more accurate work indices of sodium feldspar and other minerals.

Acknowledgements

We would like to thank Mr. Anuphong Rodsuphot from Pipakorn Co. Ltd. for his assistance on the collection of the Nopphitam feldspar samples. We also thank Dr. Kanitta Wongyai from the Mae Moh Mine, Electricity Generating Authority of Thailand for the Hardgrove grindability test.

References

Akara Mining Ltd. (n/a). Gold and silver. *Chatree Gold Mine*, Phichit, Thailand

Allis Chalmers Corporation. (1999). Size reduction and size enlargement. In R. H. Perry & D. W. Green (Eds.), *Perry's chemical engineers' handbook.* (pp. 20-1-20 -22). New York, NY: McGraw-Hill.

American Society for Testing and Materials. (1993). *ASTM D-409, Standard test method for grindability of coal by ball-race Hardgrove-machine.* Philadelphia, PA: Author.

Aplan, F. F. (1996). The Hardgrove test for determining the grindability of coal. *Lecture note in MN PR 301: Elements of mineral processing.* Department of Energy and Geo-environmental Engineering, Pennsylvania State University, State College, PA.

Aplan, F. F., Austin, L. G., Bonner, C. M., & Bhatia, V. K. (1974). *A study of grindability tests.* (Project G0111 786). United States Bureau of Mines, Washington, DC.

Barry, T. F., & Bruce, R. W. (1966). A simple method of determining the grindability of ores. *Canadian Mining Journal*, *87*, 63-65.

Bond, F. C. (1961). Crushing and grinding calculations, part I and part II. *British Chemical Engineering*, *6*, 378.

Bond, F. C. (1963). More accurate grinding calculations. *Cement, Lime and Gravel*, March issue.

Cement and Mining Technology GmbH. (2015, January 13). Wet grinding mill. Retrieved from http://cemtec.at/fileadmin/user_upload/WET_GRINDING_MILLS.pdf

Doering International GmbH. (2015, January 13). Grinding media size formula. Retrieved from http://www.doeringsinn.de/fileadmin/download/mahlkoerper/Mahlkoerperformel_nach_Bond_en.pdf

Department Primary Industries and Mines. (2007). *Minerals and rocks: their specification and commodity trade*. Bangkok, Thailand: Department of Primary Industries and Mines.

Herbst, J. A., Yi, C. L., & Flintoff, B. (2003). Size reduction and liberation. In M. C. Fuerstenau & K. N. Han (Eds.), *Principles of mineral processing* (pp. 61-118). Littleton, CO: Society of Mining Engineers.

Hogg, R. (2003). Particle characterization. In M. C. Fuerstenau & K. N. Han (Eds.), *Principles of mineral processing* (pp. 9-60). Littleton, CO: Society of Mining Engineers.

Metso Minerals. (2018). Basic in mineral processing. Denver, CO: Denver Sala Basic.

NEDO. (2003). *Industrial Management Course in Clean Coal Technology*. Center for Coal Utilization of Japan, Tokyo, Japan.

Pongprasert, T., Rujipattanapong, R., & Boonthong, T. (1994). Determination of Bond grindability work index of feldspar ore. *Proceedings of the 5th Thai Mining Engineering Conference: Mineral and Energy Industries for Economics Development*, Songkla, Thailand.

Rattanakawin, C., Phuvichit, S., Nuntiya, A., & Tontahi, T. (2005). *Value-adding and processing of feldspar of northern region, Thailand*. Bureau of Primary Industries, Department of Primary Industries and Mines, Bangkok, Thailand.

Rattanakawin, C., & Tara, W. (2012). Characteristics of Mae Moh lignite: Hardgrove grindability index and approximate work index. *Songklanakarin Journal of Science and Technology*, *34*(1), 103-107.

Rhodes, M. (1998). *Introduction to particle technology*. West Sussex, England: John Wiley and Sons.

Tenova Mining and Minerals (Pty) Ltd. (2015, January 13). Mineral processing: product. Retrieved from http://www.tenovagroup.com/pdf/brochure/ 78SAG,%20AG,%20Rod,%20Ball%20Mills.pdf