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Original Article

Characteristics of Mae Moh lignite: Hardgrove grindability index and approximate work index

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Abstract

The purpose of this research was to preliminarily study the Mae Moh lignite grindability tests emphasizing on Hardgrove grindability and approximate work index determination respectively. Firstly, the lignite samples were collected, prepared and analyzed for calorific value, total sulfur content, and proximate analysis. After that the Hardgrove grindability test using ball-race test mill was performed. Knowing the Hardgrove indices, the Bond work indices of some samples were estimated using the Aplan's formula. The approximate work indices were determined by running a batch dry-grinding test using a laboratory ball mill. Finally, the work indices obtained from both methods were compared. It was found that all samples could be ranked as lignite B, using the heating value as criteria, if the content of mineral matter is neglected. Similarly, all samples can be classified as lignite with the Hargrove grindability indices ranging from about 40 to 50. However, there is a significant difference in the work indices derived from Hardgrove and simplified Bond grindability tests. This may be due to difference in variability of lignite properties and the test procedures. To obtain more accurate values of the lignite work index, the time-consuming Bond procedure should be performed with a number of corrections for different milling conditions. With Hardgrove grindability indices and the work indices calculated from Aplan's formula, capacity of the roller-race pulverizer and grindability of the Mae Moh lignite should be investigated in detail further.

Keywords: approximate work index, Hardgrove grindability index, Mae Moh lignite,

1. Introduction

Pulverized-lignite fired thermal power plants have been implemented for many decades in Thailand. Coal pulverizers can be broadly classified into three types: hammer, horizontal and vertical mills. Hammer mill is applied to grind high moisture content brown coal. Horizontal mill, e.g. air-swept tumbling ball mill, is used to grind high ash content or low grindability coal such as lignite. Besides, a vertical mill is normally used for sub-bituminous or bituminous material. The vertical mills can be sub-classified as roll-bowl, ball-race and roller-race type mills. The Electricity Generating Authority of Thailand (EGAT) who operates the Mae Moh Lignite Mine, Lampang, Thailand, uses both ball-race and roller-race mills in pulverizing lignite for the thermal power plant at Lampang recently.

To determine the relative grindability of coal, i.e. whether it is easy or difficult to pulverize, the Hardgrove test is a standard method widely used (Klima, 1999). The Hardgrove grindability index (HGI) can be then estimated from the test. The higher the index is the easier the coal to be pulverized. However, this index can not be used to size a pulverizer and mill power directly. Only the specific energy, mill power over capacity, is a main parameter for mill sizing. Specifically, the Bond work index is suitable for utilization in many industrial grinding processes (Rhodes, 1998).

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Bond defined the work index (W_i) as the work (kWh per short ton) to reduce particle from theoretically infinite size to 80% passing 100 μm. The Bond's formula is derived from an empirical law of comminution 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 (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 were known. Aplan *et al.* (1974) and Aplan (1996) have shown a correlation between the HGI and W_i of U.S. coal though these two indices are based on quite difference test procedures. The approximate relationship is as followed:

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

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. Once the HGI has been measured, the capacity of a standard roller-race pulverizer may be estimated from the capacity graph (Aplan, 1996). This graph gives the capacity factor for any HGI value, and for any degree of fineness required for proper coal combustion in the boiler. Knowing the base capacity of a standard commercial pulverizer, its capacity for grinding any other coal can be estimated.

The purpose of this research was to carry out preliminarily tests on the grindability of Mae Moh lignite, emphasizing on the HGI and approximate W_i determination respectively.

2. Methodology

The mandatory proximate analysis, total sulfur analysis and heating value determination of the Mae Moh lignite samples were firstly performed. Then the key indices HGI and approximate W_i of those samples were determined from grindability tests. Finally, the approximate W_i value obtained from both the simplified Bond procedure and the calculation from the HGI values were compared.

2.1 Coal analyses

There are five coal seams in Mae Moh lignite field at Lampang. They are classified as J, K, Q, R and S seams. The major seams mined recently are the K and Q ones. Therefore, the lignite including various K and Q samples were collected from the Mae Moh mine site. These samples are the representatives of lignite with various calorific values and sulfur contents. There are six samples coded as K3W11, Q4W11, K3W13, Q1W13, K3W14 and Q4W14 respectively. The samples were collected, prepared and analyzed according to the American Society for Testing and Materials (ASTM, 1993) standards as following: Collection of gross sample (ASTM D-2234), Preparation of laboratory sample (ASTM D-2103), Proximate analysis of coal & coke (ASTM D-3172), Moisture in the analysis sample of coal & coke (ASTM D-3173), Ash in the analysis sample of coal & coke (ASTM D-3174), Volatile matter in the analysis sample of coal & coke (ASTM D-3175), Total sulfur in the analysis sample of coal & coke (ASTM D-3177), Calculation of coal & coke analyses from as-determined to different bases (ASTM D-3180), and Gross calorific value of coal & coke by isoperibol bomb (ASTM D-3286).

2.2 Grindability tests

In this study, there are two methods of grindability test performed Hardgrove and simplified Bond methods. For the Hardgrove test, the samples were pulverized according to the procedure described in the standard test method (ASTM D-409) for grindability of coal by the ball-race Hardgrove-machine shown in Figure 1. Briefly, a 50 g. sample of the -16+30 U.S. mesh coal was placed in the Hardgrove machine, and ground for 60 revolutions. After that the product was dry sieved, and the amount (W) of the -200 mesh was weighed. The HGI was then determined from

$$HGI = 13 + 6.93\,W \quad (4)$$

Figure 1. Ball-race Hardgrove machine.

It should be mentioned that the Hardgrove-machine approximately simulates the grinding action according to the commercial pulverizer of the roller-race type.

For the simplified Bond method, an approximate work index may be determined by running a batch dry-grinding test. The test was performed using a 25 cm diameter tumbling ball mill with material hold-up of about 10%, media loading of about 25% and a unit interstitial filling. Two kilograms of the 5 mm lignite samples were ball-milled for 10 minutes. The electrical current (I, amperes) was measured using the Volt/Am-meter during the ball-milling process. Knowing the measured current, voltage (V, volts) and power factor ($\cos \phi$) of the drawn motor; the power (P, watt) consumed by the mill was estimated from

$$P = IV \cos \phi \qquad (5)$$

Note that the samples Q1W13, K3W13 and K3W14 which have a significant difference in the HGI values were selected and used in this simplified Bond test. The feed and product of those samples were sieved using the Tyler mesh series. Then the particle size distributions were plotted in log-log scale. Knowing the specific energy and the 80% passing sizes of feed and product from this Gaudin-Schuhmann plot or those values from Equation 2, the work index was estimated from Equation 1. It should be specified that for the determination of the Bond grindability work index, the standard Bond procedure must totally be employed. The standard procedure was described at length by Dister, R.J. (n/a) and Pongprasert *et al.* (1994).

3. Results and Discussion

3.1 Coal analyses and Hardgrove grindability indices

In all coal specifications, it is important that the basis of the analyses must be known and well-stated. The following bases are commonly used in coal industry:

a) As-received – containing surface and inherent moisture.

b) As-determined – containing only inherent moisture, i.e. the moisture retained in the micro-pores of a coal.

c) Dry – no moisture available.

d) Dry ash-free – minus moisture and ash from a proximate analysis.

The proximate analysis, total sulfur and heating value of the K3W14 sample with different bases are shown in Table 1.

Characteristics of coal relevant to coal-fired power plant are customarily based on as-determined basis. Therefore the proximate analyses, total sulfur, and heating values of various samples on as-determined base are summarized in Table 2. The HGI values of the related samples are also included in this table. It appears from Table 2 that most HGI

Table 1. Proximate analysis, total sulfur and heating value of the K3W14 sample with different bases.

Analytical Parameters	As-Determined Basis	As-Received Basis	Dry Basis	Dry Ash-Free Basis
Moisture (%)	15.72	40.96	-	-
Ash (%)	13.11	9.18	15.56	-
Volatile Matter (%)	30.24	21.18	35.88	42.49
Fixed Carbon (%)	40.93	28.67	48.56	57.51
Total Sulfur (%)	3.17	2.22	3.76	4.45
Heating Value (kCal/kg)	3035	2126	3601	4264

(Air-Dry Loss in accordance with ASTM Method D-2013 = 29.95)

Table 2. Proximate analyses, total sulfur and heating values of various samples on as-determined base, and the related Hardgrove grindability indices (HGI).

Sample	Moisture (%)	Ash (%)	Volatile Matter (%)	Fixed Carbon (%)	Total Sulfur (%)	Heating Value (kCal/kg)	HGI
K3W11	9.56	44.50	22.19	23.75	2.30	2170	68
Q4W11	11.17	25.27	29.53	34.02	5.44	2301	47
K3W13	13.45	14.65	28.29	43.60	4.55	2773	43
Q1W13	9.72	15.25	32.62	42.41	4.31	2796	39
K3W14	15.72	13.11	30.24	40.93	3.17	3035	48
Q4W14	13.38	18.61	29.56	38.45	4.01	2970	46

values range from about 40 to 50, except the K3W11 sample. These values are in accordance with the HGI values of lignite; 35-50 figured by Aplan (1993). For some example, the average HGI value of lignite from well known coal seams in Ward County, North Dakota, U.S.A. is 50 (Aplan *et al.*, 1974). However, the K3W11 sample shows some deviation with higher HGI value. This may be due to clay inclusion in this lignite sample implying from high ash content in the proximate analysis. As Luckie (2000) wrote "*There is no such thing as coal; there are coals, since coal shows a high degree of variability depending upon its source and genesis*".

In Table 2, the heating values of all samples range from 2,170 to 3,035 kCal/kg (as-determined basis). All of these samples could be ranked as lignite B if the content of mineral matter is neglected. This ranking conforms to the ASTM D-388: Classification of coal by rank, i.e. as the gross calorific value is less than 3,500 kCal/kg (moist, mineral matter free basis).

3.2 Approximate worxk indices

The approximate Bond work indices of the Q1W13, K3W13 and K3W14 lignite samples are 10.57, 10.63, and 8.81 kW/STPH respectively. These approximate values obtained directly from specific energy measurements, and the 80% passing sizes of both product and feed from the Gaudin-Schuhmann plot. For example, the E_B required to pulverize the K3W14 lignite sample was 2.9251 kW/STPH, and the responding $X_{p,80}$ and $X_{f,80}$ were 308 and 1,765 µm (Figure 2). Then the approximate work index calculated from Equation 1 equals 8.81 kW/STPH. For the work indices calculated from the HGI values (Equation 3) of those corresponding samples are 15.17, 13.81, and 12.43 kW/STPH. Comparison of the approximate work indices obtained from both methods is shown in Table 3.

It can be seen from Table 3 that the higher the HGI values yields the lower the Bond work indices calculated from those corresponding values are. This observation is also valid with the approximate work indices except for the K3W13 sample. However, there is much difference in the work indices between both grindability tests. This may be due to difference in variability of lignite properties and the test procedures. For example, the HGI values of Thai lignite depend on properties such as coalification rank and inorganic compounds e.g. % ash and sulfur (Sikong and Vichitrasanguan, 1994). The grindability test procedures, especially for the simplified Bond one, may oversimplify the standard procedure. Indeed, a locked cycle ball mill test allows a determination of the energy requirement to mill lignite but the test must be performed in a steady state condition with an equilibrium circulating load. To obtain more accurate values of the Mae Moh lignite work index, the time-consuming Bond procedure and calculations (Bond, 1961 and 1963) should be applied with a number of corrections for different milling conditions.

4. Conclusion

The HGI values of the Mae Moh samples imply that most of the samples can be characterized as lignite. This characterization is in accordance with coal ranking using the gross calorific value as the criteria. The work indices calculated from the HGI values using the Aplan's formula of those representative samples are 15.17, 13.81 and 12.43 kW/STPH. However, there is much difference in the work indices derived from the Hardgrove and simplified Bond grindability tests. This may be due to difference in variability of lignite properties and the test procedures. To enhance and strengthen the approximate work index results, the standard Bond procedure must totally be employed. With useful data from this preliminary study, especially Hardgrove grindability indices and the work indices calculated from Aplan's formula, the

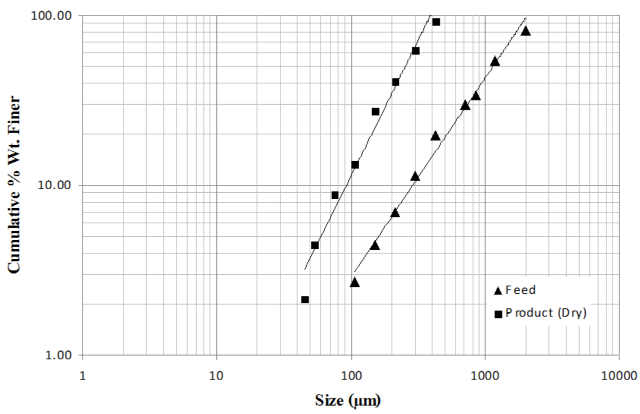

Figure 2. Size distributions of the K3W14 lignite feed and product samples on the Gaudin-Schuhmann plot.

Table 3. Comparison of work indices (W_i) obtained from the calculation of the Hardgrove grindability (HGI) values and the simplified Bond method.

Sample	HGI	Calculated W_i from HGI (kW/STPH)	Approximate W_i (kW/STPH)
Q1W13	39	15.17	10.57
K3W13	43	13.81	10.63
K3W14	48	12.43	8.81

capacity of the roller-race pulverizer and grindability of the Mae Moh lignite should be investigated in detail further.

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References

American Society for Testing and Materials. 1993. Annual Book of ASTM Standards, ASTM, Philadelphia, U.S.A.

Aplan, F.F. 1993. Coal properties dictate coal flotation strategies. Transactions of American Institute of Mining, Metallurgical, and Petroleum Engineers. 294, 83-96.

Aplan, F.F. 1996. The Hardgrove test for determining the grindability of coal. In Lecture Note on MN PR 301: Elements of Mineral Processing, Department of Energy & Geo-environmental Engineering, Pennsylvania State University, State College, Pennsylvania, pp. 92-93.

Aplan, F.F., Austin, L.G., Bonner, C.M. and Bhatia, V.K. 1974. A study of grindability tests, Report to U.S. Bureau of Mines, Project G0111786.

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.

Dister, R.J. n/a. How to determine the Bond work index using lab ball mill grindability tests, E&MJ, February, 42-45.

Hogg, R. 2003. Principles of Mineral Processing, In M.C. Fuerstenau and K.N. Han, editors, Society of Mining Engineers, Colorado, pp. 9-60.

Klima, M.S. 1999. Introduction to coal processing. In Lecture Note on MN PR 424: Coal Preparation, Department of Energy & Geo-environmental Engineering, Pennsylvania State University, State College, Pennsylvania.

Luckie, P.T. 2000. Personal Communication, Department of Energy & Geo-environmental Engineering, Pennsylvania State University, State College, Pennsylvania.

Pongprasert, T., Rujipattanapong, R. and Boonthong, T. 1994. Determination of Bond grindability work index of feldspar ore. In Proceedings of the 5th Thai Mining Engineering Conference: Mineral and Energy Industries for Economics Development. pp. 4-34 - 4-46.

Rhodes, M. 1998. Introduction to Particle Technology, John Wiley & Sons, West Sussex, U.K. pp. 241-265.

Sikong, L. and Vichitrasanguan, P. 1994. Hardgrove grindability index and Vickers hardness of Thai lignite. In Proceedings of the 5th Thai Mining Engineering Conference: Mineral and Energy Industries for Economics Development. pp. 5-44 - 5-53.