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The bond work index of binary and ternary mixtures of ceramic raw materials

Haluk Celik*

Usak University, Faculty of Fine Arts, Department of Ceramic, 1 Eylul Campus, 64200-Usak, Turkey

Size reduction of minerals by grinding being an energy-intensive unit operation is widely used in the preparation of raw materials for manufacturing of ceramic products. This paper presents briefly the standard Bond grindability testing method, which is widely used for prediction of milling energy requirements. The most frequently used ceramic raw materials, namely kaolin, quartz, and sodium feldspar were chosen for laboratory experiments with standard particle size ranges and the Bond method was applied to them singly, and also their binary and ternary mixtures. The Bond work indexes (W_i) of these singly ground ceramic raw materials were defined as 10.38, 12.49, and 11.85 kWh/t, respectively. The Bond work indices of the both binary and ternary mixtures containing softer kaolin mineral were found to be greater than the calculated work indices of the individual minerals. The work indices of the ternary mixtures were increased significantly from 12.70% to 24.31% with respect to the calculated work index values when kaolin was put in the mixtures at progressively increased amounts of 33.3% and 60%, respectively. The statistical assessments in order to determine the repeatability of the grinding tests pointed out those experiments gave replicated results with standard deviation values between 0.381 and 0.882 and coefficient of variations values between 3.05% and 6.17%.

Key words: Bond work index, Ceramic raw materials, Grinding, Industrial minerals.

Introduction

Ceramics are products made from inorganic materials which are first shaped and subsequently hardened by heat. Many ceramic raw materials require crushing or disintegrating followed by dry or wet grinding to various degrees of fineness before they can be used in ceramic manufacture [1] in order to reduce the average particle size of materials, to liberate impurities, to reduce the porosity of particles, to modify the shape of particles and to increase the content of colloids [2]. Compound formation during firing and densification during sintering require diffusion between neighboring particles. Diffusional processes are proportional to the square of the particle size. The most common method for reducing particle size is ball milling [3] mainly because of the simple construction and application [4]. The ground mixture is then spray dried, pressed and fired to obtain ceramic products. Most of the energy is consumed in the grinding operations for the ceramic industry. As is known, some of the energy during grinding is converted to heat that is not utilized fully in the grinding process. Thus, grinding is not a very efficient operation and it needs to be taken care of in detail. However, it is possible to set up a grinding system with a low energy consumption and higher efficiency [5]. In mineral processing operations, comminution can account for 55-70% of the total power consumption [6]. 5% of the total energy consumption of developed countries is directed to crushing and grinding processes [7].

Ceramic raw materials are generally ground to a required fineness as mixtures prepared according to some recipes to provide a consistent feed to a process in terms of a uniform assay. When several different materials of varying grindabilities are mixed prior to grinding, the hardness of the ore blend is usually estimated as the average of the material grindabilities. It is often suspected whether this is true or not [8]. Grinding characteristics of ceramic raw material mixtures have been studied by several researchers to determine the variation of the grindability of a ceramic raw material blend as a function of the blend composition [5, 8, 9, 10, 11]. Ipek *et al.* [9] applied the Bond method of grindability to ceramic raw materials (quartz, kaolin and potassium feldspar) and their binary and ternary mixtures at a test size of 150 μm. They established that separate grinding of ceramic raw materials required less specific energy input than grinding them in admixtures. They stated that the Bond work indices of the admixtures containing a softer component are greater than the weighted average of the work indices of the individual components in the mixture.

At present, the industry standard for forecasting the energy required for grinding is to use empirical relationships developed in 1952 and modified in 1961 by Bond to relate laboratory milling test results to predict industrial scale energy consumption in terms of a Bond Work Index (W_i) [12]. Its use as an industrial standard is very common, providing satisfactory results in all industrial applications [13]. The standard Bond grindability test is a closed-cycle dry grinding and screening process, which is carried out until steady state conditions are obtained [14]. The W_i of a material is defined as the energy needed to reduce one metric tonne

*Corresponding author:
Tel : +90-276-221-2138
Fax: +90-276-221-2139
E-mail: haluk.celik@usak.edu.tr

of that material from a notional infinite size to a d_{80} size of 100µm, and is calculated from the following equation :

$$W_i = \frac{49}{P_i^{0.23} \cdot G_{bp}^{0.82} \cdot \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}} \right)} \quad (1)$$

The W_i obtained by this equation is a measure of a material's resistance to breakage and is given in kWh per ton. P_i is the test sieve size closing the circuit, G_{bp} is the average of the net grams of undersize produced per mill revolution (g/rev) during the last three grinding cycles, P_{80} is 80% passing size (µm) of the product, and F_{80} is 80% passing size (µm) of the feed.

In designing and optimizing a milling circuit using W_i, the following equations (2) and (3) are used:

$$W = 10 W_i \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right) \quad (2)$$

$$P = T * W \quad (3)$$

where W is the predicted mill energy consumption (kWh/ton), T is the throughput of new feed (ton/h) and P is the power draw (kW). It should be noted that the power calculated by the Bond equation is the power that should be delivered to the mill and does not include motor or drive-train losses [15].

The objective of this study is to compare the work indices of singly ground most frequently used ceramic raw materials namely, kaolin, sodium feldspar and quartz with the work indices of their binary and ternary mixtures. Statistical assessments were also accomplished at the end of the study in order to determine the repeatability of the grinding experiments.

Experimental

Materials

The ceramic raw materials used for the Bond grindability tests were kaolin from Ballkesir-Turkey, sodium feldspar obtained from Aydln-Turkey and quartz from Aydln-Turkey. Chemical analyses of these materials determined by X-ray fluorescence in a Spectro IQ equipment are given in Table 1. Specific gravity of the samples (see Table 2) was obtained

Table 1. Chemical analyses of the ceramic raw materials (wt%)

	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	Cr_2O_3	LOI*	Total
Kaolin	82.14	11.92	0.26	0.24	0.10	0.10	0.10	0.11	0.15	0.06	0.05	4.77	100.00
Feldspar	68.32	18.36	0.31	0.29	0.91	0.54	10.03	0.47	0.25	-	-	0.53	100.00
Quartz	99.27	0.29	0.03	-	0.03	0.02	0.18	0.02	-	-	-	0.16	100.00

*Loss on ignition

Table 2. The characteristics of the mill and test conditions

Mill

Diameter, D (cm)	Lenght, L (cm)	Volume, V^1 (cm^3)	Speed (rpm)	Critical speed N_c^2
30.5	30.5	22,272.5	70	76.59

Mill charge

Diameter, d (mm)	Number	Distribution by weight %	Total mass (g)	Specific gravity (g/cm^3)	Bulk density (g/cm^3)	Fractional ball filling f_b^3
38.10	43	44.3	22,647.8	8.05	4.83	0.21
31.75	67	39.9				
25.40	10	3.1				
19.05	71	9.1				
12.70	94	3.6				
Total	285	100.0				

Powder charge

Sample	Specific gravity (g/cm^3)	Weight, (g) (for their individual test)	Fractional powder filling f_p^4	Powder-ball loading ratio U^5
Kaolin	2.61	2935	0.084	1.00
Na-feldspar	2.62	2948		
Quartz	2.68	3015		

$$V^1 = \pi \left(\frac{D}{2} \right)^2 . L \qquad N_c^2 = \frac{42.3}{\sqrt{D-d}} \qquad f_b^3 = \left(\frac{mass\ of\ balls\ /\ ball\ density}{mill\ volume} \right) x \frac{1.0}{0.6}$$

$$f_p^4 = \left(\frac{mass\ of\ powder\ /\ powder\ density}{mill\ volume} \right) x \frac{1.0}{0.6} \qquad U^5 = \frac{f_p}{0.4 f_b}$$

by means of a helium pycnometer (Quantachrome Multipycnometer), whereas hardness of the sample was measured by a hardness pen. The quartz and sodium feldspar samples, having Mohs hardness indices of 7 and 6, respectively, are relatively harder than the kaolin sample having a Mohs hardness of 3.

Methods

Initially, kaolin, sodium feldspar and quartz samples were separately ground in the Bond mill, and then the Bond grindability tests were conducted with;

a - binary mixtures of kaolin:Na-feldspar, kaolin : quartz and Na-feldspar : quartz mixed in the ratios of 1 : 1 by weight,

b - ternary mixtures of the ceramic raw materials kaolin : quartz : Na-feldspar mixed in the ratios of 1 : 1 : 1, 2 : 1 : 1, 3 : 1 : 1, and 1 : 2 : 2 by weight.

The stainless steel mill used for the tests was a standard Bond ball mill with an internal diameter and length of 30.5 cm. The characteristics of the Bond mill used in grinding tests and test conditions are outlined in Table 2. For all of the tests, the mill was operated at a fixed speed of 70 rpm and charged with 285 stainless steel grinding balls ranging from 12.7 to 38.1 mm diameter with a total weight of 22,647.8 kg. The ball voids were about 40% of the ball charge (4686 cm^3). This measurement was made by displacement of water. The volume of the ball charge with voids was 21.04% of the total volume of the mill. In each case, the mil was loaded such that 100% of the interstitial void volume of the ball charge was filled with test samples at the beginning of the experiments.

The standard Bond grindability test has been described as follows [14, 15, 16, 17, 18, 19]. The Bond grindability tests were conducted with 100% −3.35 mm dry feed materials. The amount of material for each test was 700 ml. For the first grinding cycle, the mill was started with an arbitrarily chosen number of mil revolutions. At the end of each grinding cycle, the entire product was discharged from the mill and screened on a 106 μm test sieve (P_i). The oversize fraction (R) was returned to the mill for the second run together with an additional quantity of minus 3.35 mm fresh feed material (U) to make up the original weight corresponding to 700 ml.

In the standard Bond test at a standard 250% circulating load, 28.57% of the weight of the mill feed (M) required to be ground under the test sieve size closing the circuit as calculated from Eq. 7:

$$\frac{R}{U}=2.5 \tag{4}$$

$$U+R=M \tag{5}$$

where R: weight of the test sieve oversize (g), U: weight of the new feed (g), and M: weight of the mill feed (g). From Eqs. (4) and (5) it follows that:

$$R=\frac{2.5}{3.5}M \tag{6}$$

$$U=\frac{1}{3.5}M \tag{7}$$

The weight of ground material passing through 106 μm screen per unit of mill revolution (G_{bp}), called the ore grindability of the cycle, was then calculated and the number of revolutions required for the second run, equivalent to a 250% recirculating load of particles coarser than the 106 μm was estimated. After the second cycle, the same procedure of screening and grinding was continued until G_{bp} became constant for the last three grinding cycle and, steady-state grinding conditions were said to prevail. After reaching equilibrium, the average value of the last three cycles was taken as the standard Bond grindability (G_{bp}). The products of the total final three cycles were combined to form the equilibrium test product. Sieve analysis was carried out on the material and the results were plotted to find the 80% passing size of the product (P_{80}). Finally, the work index (W_i) was calculated from the empirical equation 1.

In order to determine the repeatability of the grinding tests, arithmetical average (X) (Eq. 8), standard deviation (σ) (Eq. 9), and coefficient of variations (C_v) (Eq. 10) of the W_i values of the five replicate grinding experiments were calculated for each single ground and mixed grinding test (n is 5, the number of grinding tests for each separate batch). The standard deviation (σ) shows how much variation there is from the average. A low standard deviation indicates that the data points tend to be very close to the average whereas a high standard deviation indicates that the data are spread out over a large range of values. The coefficient of variations (C_v) is defined as the ratio of the standard deviation to the arithmetical average.

$$X=\frac{\sum W_i}{n} \tag{8}$$

$$\sigma=\sqrt{\frac{\sum W_i^2-\frac{(\sum W_i)^2}{n}}{n-1}} \tag{9}$$

$$C_v=\frac{\sigma}{X}*100 \tag{10}$$

Results and Discussion

Fig. 1 presents the feed cumulative size distributions of the tested ceramic raw materials. As seen from Fig. 1, the 80% passing size values (F_{80}), which were used in the work index equation 1, of kaolin, quartz and feldspar are 2447, 2976, and 2800 μm, respectively. The percentage of the material in the feed under the 106 μm test sieve size (P_i), which was used throughout the single grinding tests in order to calculate the net amount of materials produced to the size of under P_i, 10.24, 6.56, and 8.42 μm, respectively. For the binary and ternary mixture grinding

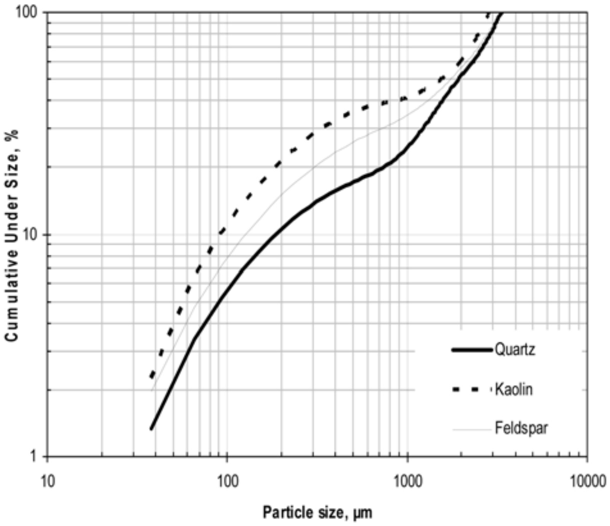

Fig. 1. The cumulative feed size distribution of the raw materials.

Table 3. Bond grindability test results of ceramic raw materials

	F_{80} (µm)	P_{80}* (µm)	G_{bp}* (g/rev)	Experimental W_i* (kWh/t)	Calculated W_i (kWh/t)
Kaolin (K)	2447	81,67	2,029	10,38	-
Quartz (Q)	2976	125,48	2,176	12,49	-
Feldspar (F)	2800	112,48	2,155	11,85	-
1K : 1F	2620	120,11	2,103	12,71	11,11
1K : 1Q	2736	93,45	1,595	13,55	11,43
1F : 1Q	2875	112,32	2,046	12,31	12,17
1K : 1Q : 1F	2744	101,32	1,776	13,04	11,57
2K : 1Q : 1F	2668	90,34	1,593	13,33	11,27
3K : 1Q : 1F	2624	83,38	1,443	13,79	11,09
1K:2Q:2F	2798	115,31	2,113	12,23	11,81

*Average of five tests

tests, the values of F_{80} (given in Table 3) and the percentage of materials under the test sieve size (P_i) were established from the sieving test results at the beginning of each batch grinding experiment.

Table 3 depicts the Bond grindability test results of single ground, binary and ternary mixtures of kaolin, quartz and Na-feldspar. Experimental work indices are the average of five replicate grinding tests given in Table 4. Calculated work indices for the binary and ternary mixtures of the minerals are calculated from the work indices of the singly ground materials on weight fraction basis.

From Table 3, it can be seen that for a given test sieve size, the bond work index of singly ground materials for quartz is highest followed by sodium feldspar and kaolin is the least as expected on account of their hardness value on the Mohs scale. At 250% circulating load and $P_i = 106$ µm test sieve size, the corresponding values being 12.49 kWh/t, 11.85 kWh/t, and 10.38 kWh/t. As can be seen from Table 3 that when a softer material kaolin was added to the mixtures, the work index of the binary mixtures of 1K : 1F and 1K : 1Q were increased to 12,71 and 13,55 kWh/t with respect to the calculated work index values, corresponding to a rising rate of W_i 14.39% and 18.54%, respectively. In the case of binary mixtures of 1F : 1Q, which contained minerals of hardness values close to each other, experimental and calculated W_i values were determined to be substantially the same. The work indices of the ternary mixtures were increased gradually from 12.70%, and 18.24% to 24.31% by a significant amount with respect to the calculated work index values when kaolin was added to the mixtures in progressively increased amounts of 33.3%, 50% and 60%, respectively. The earlier results are in line with the results available from the literature (8, 9). The explanation of these results can be made as the presence of relatively softer kaolin particles in both the binary and ternary mixtures prevented the quartz and feldspar minerals from been ground. Furthermore, the reason why work indices of mixtures are higher than the individual work indices of raw materials can be explained by the cushioning effect created by the easily ground parts of kaolin which stick on the ball and mill walls due to moisture (8). The unfavorable effect of kaolin on the mixture grindability decreased when the amount of kaolin was decreased in the mixture of 1K : 2Q : 2F. In this instance, the work indices increased 3.55% with respect to the calculated work index.

The standard deviation (σ), coefficient of variations (C_v) and W_i values of the five replicate grinding experiments are presented in Table 4. As can be seen from Table 4 the

Table 4. The Bond indices (W_i), standard deviation (σ) and coefficient of variations (C_v) values of the five replicate grinding experiments

	Singly Ground			Binary Mixtures			Ternary Mixtures			
	Kaolin (K)	Quartz (Q)	Feldspar (F)	1K : 1F	1K : 1Q	1F : 1Q	1K : 1Q : 1F	2K : 1Q : 1F	3K : 1Q : 1F	1K : 2Q : 2F
Wi, kWh/t	11,01	12,90	12,06	12,35	12,82	12,74	13,17	12,13	13,04	12,29
	9,96	11,98	11,63	12,19	13,97	12,86	12,05	13,20	13,25	12,50
	10,16	12,58	11,86	13,55	12,98	12,73	13,21	13,11	13,38	12,08
	10,43	12,22	12,48	13,29	13,89	11,46	12,64	14,18	14,86	13,02
	10,34	12,76	11,23	12,15	14,08	11,78	14,13	14,02	14,42	11,24
σ	0,396	0,381	0,467	0,662	0,598	0,646	0,770	0,882	0,801	0,653
C_v,%	3,81	3,05	3,94	5,21	4,41	5,24	5,91	6,17	5,81	5,34

low values of both the standard deviation and the coefficient of variations point out the repeatability of the grinding studies. It may be worthy to remark that the standard deviation and coefficient of variation values slightly increase in parallel with the increasing number of minerals in the mixtures. Although, the necessary meticulousness was used throughout the studies, this result may be actualized as a consequence of a somewhat heterogeneous texture in binary and ternary mixtures when compared with singly ground minerals.

Conclusions

The following facts were established from the laboratory Bond grinding experiments:

• As results of the average of five replicate grinding tests, the bond work indices (W_i) of singly ground quartz, sodium feldspar and kaolin minerals were assigned as 12.49 kWh/t, 11.85 kWh/t, and 10.38 kWh/t, respectively at a 250% circulating load and 106 μm test sieve size closing the circuit.

• When the relatively softer kaolin mineral was added to the binary and ternary mixtures of ceramic raw materials, W_i values increased when compared with the calculated W_i values.

• The rising rate of W_i with respect to the calculated work index was about 13.55% for the binary mixtures of 1K : 1Q, whereas it increased gradually 12.70%, 18.24% and 24.31% in parallel with the increasing amount of kaolin in ternary mixtures of 1K : 1Q : 1F, 2K : 1Q : 1F, 3K : 1Q : 1F, respectively.

• In the light of the above findings it can be concluded that the relatively softer minerals such as kaolin put in mixtures of ceramic raw materials may have an adverse influence upon the energy required for grinding.

• The energy consumption in the case of the separate grinding of soft and hard minerals and then blending the ground materials must be confronted with the traditional application of grinding the ceramic raw materials in mixtures taking into account the additional need of a ball mill at plant scale application.

• It was deduced from the statistical assessments that reproducible results were obtained from the grinding experiments.

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