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CORRELATION BETWEEN BOND WORK INDEX AND MECHANICAL PROPERTIES OF SOME SAUDI ORES

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The crushing energy in mineral processing industry is usually determined by empirical Bond index, regardless of the mechanical properties of a rock. Although several attempts have been made to obtain the comminution energy based on theoretical approaches, it would be beneficial to examine this relation based on physical concept. In this paper, some Saudi samples of bauxite, kaolinite, granodiorite, magnetite, granite, feldspar and quartz were tested for hardness, abrasion, compressive strength and modulus of elasticity and the bond work index of these samples were estimated. The value of Bond work index of the above samples has shown a variation from 10.8 kwh ton-1 for bauxite (high abrasion value and low compressive strength) to 20.4 kwh ton-1 for granite (low abrasion value and high modulus of elasticity). The correlation between the abrasion value(X2) and work index (Wi) is found to be Wi = -1.8 Ln (X2) + 11.5 with correlation coefficient of 0.80.

KEYWORDS: *Bond work index – Mechanical properties of rocks – Grinding energy- Crushing resistance*

1- INTRODUCTION

Comminution in a mineral processing plant, or mill, involves a sequence of crushing and grinding processes [1-2]. In order to design the comminuting process of a rock, the required energy for crushing and grinding of the rocks must be calculated. This energy is estimated considering size reduction occurring in sizes of rocks. It is now generally accepted that the established relationships between energy and size reduction can be expressed using the following equation [3]:

$$dE' = -K dD / D^n \qquad \text{Eq. (1)}$$

Where E' is the specific energy that is necessary to introduce the new surface energy, K is a constant, D is the particle size (µm), and n is a value describing behavior in different size ranges.

According to Eq. (1) comminuting energy is estimated based on experimental methods rather than rock mechanical properties [3].

There are only two approaches to find out the energy consumption of a rock ground from infinite size to 100 microns or even down to this. The first one, which has been widely accepted approach, is Bond's grindability test and the second one is Hardgrove index, which generally used for coal. The Bond's grindability test can be used to determine the work index of any type of ore or material. But the process is tedious and long time consumption. Hardgrove index and brittleness test can be carried out easily on only those ores or rocks or materials, which are soft, friable and brittle [1-3].

Indices with which the crushing resistance or the grindability in a wide meaning is expressed include the Rittinger number, crushing resistance, Hardgrove index and Bond work index. The Bond work index is regarded as one of the crushing resistance; it can therefore be presumed that the Bond work index is correlated to the mechanical properties of materials [4].

Literature review on impact crusher performance in relation to machine configuration and operational conditions, by experimental work and mathematical modeling is given by studied rock failure under tensile stress conditions under impact forces. The Bond grindability test has been widely used for predictions of ball and rod mill energy requirements and for selection of plant scale comminution equipment [5].

In most mining operations, blasting, crushing, and grinding are necessary parts of the comminution process. Quick and accurate methods for estimating the respective costs for each step of the comminution process are needed to properly optimize the entire comminution process and the overall mining operation.

The ball mill is a common piece of equipment in grinding circuits. Modeling the grinding process in a ball mill is a complex task. Balls and individual particles of varying sizes and geometries collide at various angles and magnitudes. The process is further complicated by the production of countless offspring particles. To simplify the task of modeling this process, the many collisions occurring in the mill can be considered a collection of single impacts. Viewing the milling process as the sum of individual impact events leads to the study of comminution by means of single-particle impacts [4]. The main object of this contribution is to focus on the portion of the comminution process which deals with the prediction of the energy consumption due to the grinding portion of the comminution processes.

2- EXPERIMENTAL WORK OF SOME MECHANICAL PROPERTIES OF THE STUDIED MATERIALS

The energy consumed in the process of comminution depends on both the mechanism of comminution and the mechanical properties of the materials being ground. So, it is interesting to study the effect of the essential ones of these properties on the energy efficiency of grinding process.

In this investigation, some Saudi samples from bauxite, kaolinite, granodiorite, magnetite, granite, feldspar and quartz were tested for hardness, abrasion, compressive strength and modulus of elasticity, , and the work index is estimated.

2.1 Hardness Test

The Rockwell test measures hardness by using diamond cone indenter. The indentation is measured after a lighter initial load is applied and after a heavier load is applied. This test is carried out on a machine that records each depth and calculates the hardness factor. The evaluator must consider the fundamental properties of a sample before it is testing to ensure it is being evaluated using the proper loading. The hardness is reported on one of the scales A through G; depending on what material is being tested and which loading is used in the procedure. Three specimens of each studied material were tested. Each specimen with dimensions of 10*10*2 cm was prepared and polished for testing. The polished surface of each specimen was divided by grids to 16 spots [6-8]. Rockwell testing machine is used to measure the hardness of the material at these spots. A preliminary load (P_o) equals to 10 kg, and an additional load (P) equals to 52.5 kg, for soft materials { kaolinite, Granodiorite and bauxite } and 187.5 kg for hard materials { magnetite, feldspar, granite and quartz} were applied to the test specimen. The penetrating part of the machine consists of a diamond cone with edges of (105^o). The Rockwell- C-Hardness is expressed by the following equation:

$$HRC = 100 - e/0.002$$

Where, e is the remaining depth of indentation after the additional load has been removed

The average Rockwell hardness for the three specimens of each studied material was calculated.

2.2 Abrasion Test

Abrasiveness is the capacity of the rock to wear away by the contact surface of another body that is harder and in the rubbing or abrasive process during movement. The factors that enhance abrasive capacity of ores are; hardness, shape and size of the grains and the porosity of the rocks [7].

Four specimens of 7* 7* 3 cm dimensions were prepared from each bulk sample of the different studied materials. The specimens were carefully surface finished to obtain parallel and smooth faces. An abrasion substance of washed and dried sand of –630 + 500 μm is being continuously fed under each test specimen. Two test specimens are fixed in a two holders and slowly rotated during the test in order to ensure its uniform wear.

As soon as the abrasion disc has completed a standard number of 290 revolutions under a constant standard load of 18 kg, the machine is automatically stopped.

The abrasiveness of the tested rock was accepted to be as the ratio of loss in weight to the cross sectional area of the tested specimen gm cm^{-2} [4-6]. The experimental results of the different studied materials were treated statistically and the average value of the abrasion was obtained.

2.3 Compressive Strength and Modulus of Elasticity Test

Specimens were prepared and tested for compressive strength and modulus of elasticity by using a universal testing machine. The tested specimens were cylindrical shape each of 5 cm diameter, and 10 cm height as shown in Figure 1, carefully finished to obtain parallel and smooth faces to ensure that the end faces are perpendicular to the longitudinal axis of the specimens. Also, lateral and axial strain gauges are used to obtain the stress strain curve. Three specimens of each studied material were broken uniaxially after drying in an electric oven at 105^oc for 24 hours to ensure testing under uniform conditions. The stress strain curve for each sample is plotted. The average value of the compressive strength as well as modulus of elasticity was estimated as mentioned in the literature [8-10].

Figure 1: Uniaxial compression test machine

3- STANDARD BOND TESTS

The Bond's standard ball mill is used to determine the work index value of different samples. The Bond work index is defined as the kilowatt-hours per short ton required to break from infinite size to a product size of 80% passing 100 µm. If the breakage characteristics of a material remain constant over all size ranges, the calculated work index would be expected to remain constant since it indicates the resistance of material to breakage. Nevertheless, for most naturally raw materials differences exist in the breakage characteristics depending on particle size, which can result in variations in the work index depending on the grind size. In this way, work index values are usually obtained for some specific grind size that characterizes the grinding operation to design or under evaluation.

This study was carried out in a standard bond ball mill 305 mm x 305 mm size in mineral processing laboratory, in the mining engineering department at King Abdulaziz University, KSA as shown in Figure 2. Grinding media of steel balls weighing 20.5 kg has been used. The details of the mill charge are given in Table 1.

Figure 2: Laboratory Bond ball mill

Table 1 Bond mill charge distribution

Ball diameter, inch	No. of balls	Distribution, %
1 ½	25	8.8
1 ¼	39	13.7
1	60	21.0
7/8	68	23.9
3/4	93	32.6

The standard Bond grindability test is a closed-cycle dry grinding and screening process, which is carried out until steady state conditions are obtained [11-14].

The materials of 700 cm^3 volume sample with the balls was charged to the ball mill and ground initially at 100 revolutions. The ground sample was screened with the test sieve and the undersize sample was weighed and fresh unsegregated feed was added to the oversize to bring its weight back to that of original charge. The numbers of revolution required was calculated from the results of the previous period to produce sieve undersize equal to the 1/3.5 of the total charge in the mill. The grinding period cycles were continued until the net grams of sieve undersize produce per mill revolution reaches equilibrium. Then the undersize product and circulating load was screen analyzed and the average of the last three net grams per revolution (Gbp) is the ball mill grindability. The test mesh used was 100 mesh (150 μm) [14-16]. The Bond work index W_i was calculated from Equation (2)

$$W_i = 44.5/(P_1)^{0.23} \text{ X } (Gbp)^{0.82} \left[10/(P_{80})^{0,5} - 10/(F_{80})^{0.5}\right] \quad (2)$$

Where:

F_{80} is the size in (μm), at which 80 percent of the new feed to ball mill passes,

P_{80} is the size in (μm), at which 80 percent of the last cycle sieve undersize product passes, and

P_1 is the opening in (μm), of the sieve size tested

4. RESULTS AND DISCUSSION

Table 2 presents the mechanical properties of the studied materials, which include hardness, abrasion, compressive strength and modulus of elasticity. It should be noted that, from the previous studies, these properties are the most important affecting ones on the process of comminution [11]. Also, samples location in KSA and Bond's work index value of the tested materials are listed in Table. 3.

The effect of hardness of the different studied materials on their Bond work index was illustrated in Figure 3. It is noticed from this figure that the work index increases with increasing the hardness of the material according to Equation (3).

$$W_i = 3.9 \,Ln(X_1) + 2.3 \qquad R = 75\% \quad (3)$$

Where X_1= Hardness, rock well value

R=Correlation coefficient

Table 2 Mechanical properties and Bond's work index of the tested materials

Material properties / Material Type	Compressive strength (MPa)	Abrasion, (gm cm^{-2})	Hardness, rockwell value	Modulus of elasticity, (GPa)	Bond's Work Index, (kwh ton^{-1})
Bauxite	36.1	1.48	6.59	25.6	10.8
Kaolinite	58.3	0.795	13.71	32.2	11.6
Granodiorite	71.6	0.347	18.25	41.8	12.7
Magnetite	98.4	0.064	29.59	61.3	14.75
Feldspar	112.6	0.182	37.75	86.9	17.06
Granite	217.1	0.016	47.63	91.7	20.4
Quartz	181.5	0.023	56.15	77.8	16.6

Table 3 Bond's work index value of the tested materials

Material properties / Material type	Location in KSA	Bond's Work Index, (kwh ton^{-1})
Bauxite	Al Zubirah	10.8
Kaolinite	Al Zubirah	11.6
Granodiorite	Al Souk	12.7
Magnetite	Al Sawween	14.75
Feldspar	Gabel Saudda	17.06
Granite	Nagraan	20.4
Quartz	Mahd Al Dahab	16.6

This behavior may be attributed to the highly compact grains and hence low porosity, and hence prevention of energy leakage through voids. This means that most of energy consumed is executed in grinding process. On contrast, the low hardness material has high porosity, less cohesion force between particles which leads to the increase of energy dissipation through voids.

Figure 4 shows the effect of abrasion of the different tested materials on their bond work index. It is obvious from this figure that in general, the work index decreases with increasing the abrasion of material according to Equation (4).

$$W_i = -1.8 \, Ln(X_2) + 11.5 \qquad R = 80\% \qquad (4)$$

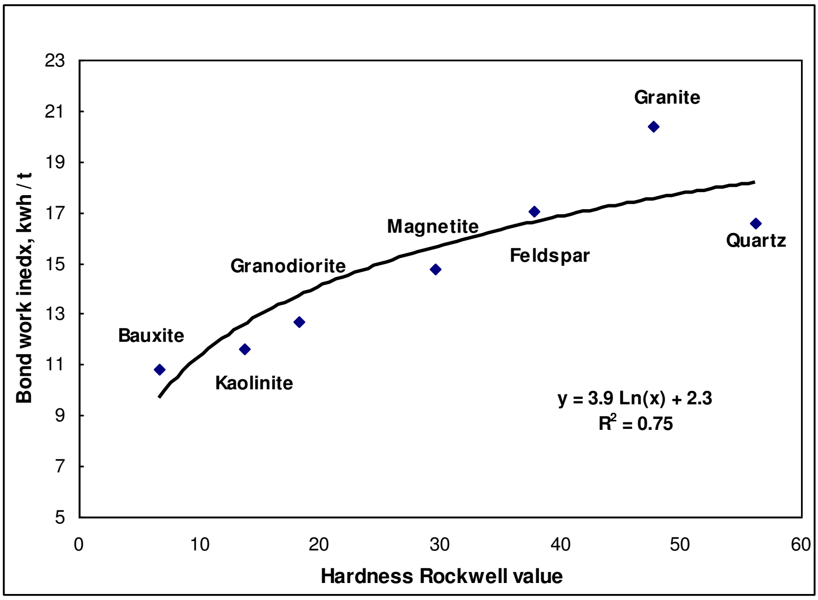

Figure 3: Effect of hardness of the different studied materials on Bond work index

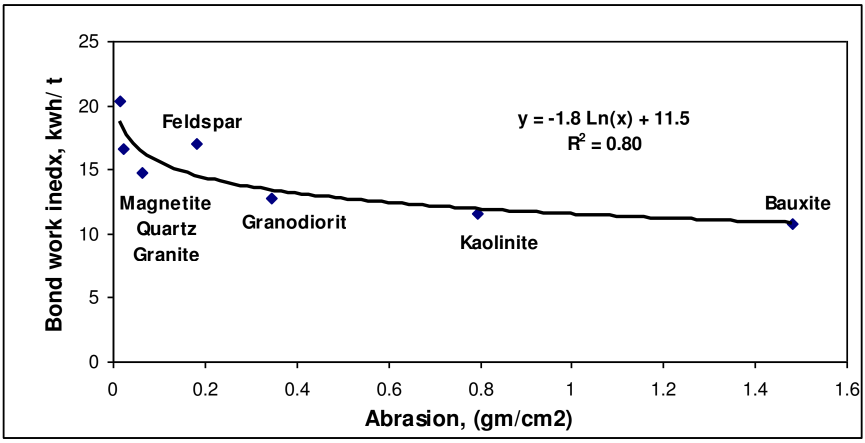

Figure 4: Effect of abrasion of the different studied materials on Bond work index

This behavior may be attributed to the mineralization formation of these materials (less cohesion between grain particles), which lead to main matrix surrounded by weak bond and weak cementing materials between grains. This structure facilitates the crushing behavior of rate.

Figure 5 illustrates the relationship between the compressive strength of the tested materials and the Bond work index. It is indicated from this figure that in general, the Bond work index increases with increasing the compressive strength according to Equation (5).

$$W_i = 5.7 \, Ln(X_3) - 9.5 \qquad R = 81\% \qquad (5)$$

Where X_3 = Compressive strength, MPa,

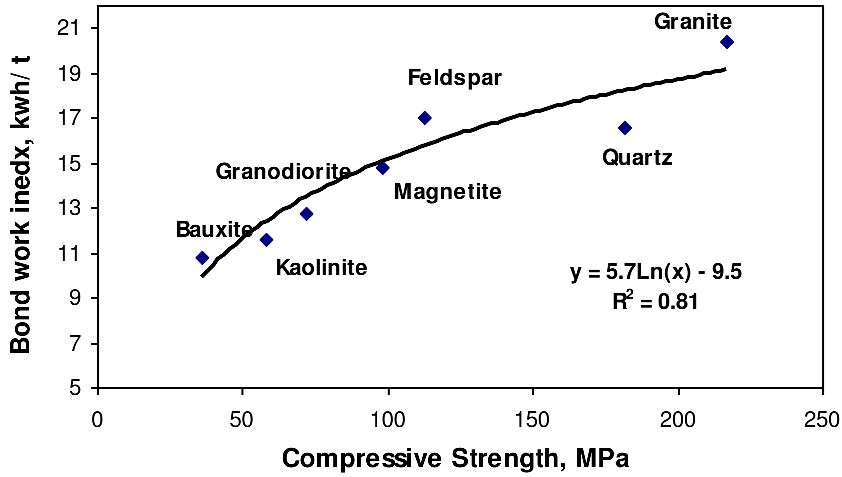

Figure 5: Effect of compressive strength of the different studied materials on Bond work index

The interpretation of this relation may be attributed to the highest compressive strength gives the lowest friability value and grindability index which leads to more energy is needed to grind. On the other hand, materials having low compressive strength showed low energy needed as it has cleavages and bedding planes.

The same trend in Figure 6 is analogous to Figure 5, which illustrates the relationship between the modulus of elasticity and the bond work index of the tested materials according to Equation (6).

$W_i = 6.3 \text{ Ln}(X_4) - 10.6$ R = 90% (6)

Where X_4=Modulus of elasticity, GPa.

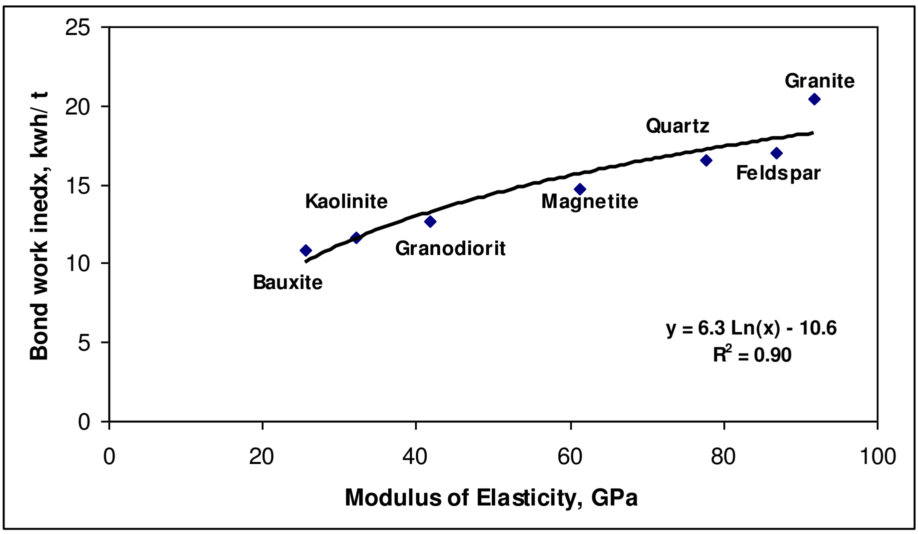

Figure 6: Effect of modulus of elasticity of the different studied materials on Bond work index

The high work index of magnetite, quartz, feldspar and granite, is due to its strong interlocking matrix and micro-crystalline structure, whereas bauxite has larger crystals and high porosity, which leads to low work index value [1].

Modulus of elasticity is a measure of structure insensitive property and it makes a contribution to the elastic strain energy in fracture phenomena. Since part of the strain energy stored in specimen up to a fracture is converted into the new surface energy fractured product. The modulus of elasticity also affects substantially on the size of fractured product. Furthermore, it is associated with the rate of crack propagation of the impact wave.

CONCLUSION

Attempts to correlate Bond work index values to mechanical properties of the tested materials were made to create reasonable predictions of future grinding circuit productivity.

There is a direct proportionality between, the Bond work index and both the compressive strength, modulus of elasticity and the hardness of the materials. While, the Bond work index decreases with increase the abrasion values of the materials.

A good correlation is found between the Bond work index and both of compressive strength and modulus of elasticity according to equation. $W_i = 5.7 \text{ Ln } (X_3) - 9.5$ and $W_i = 6.3 \text{ Ln } (X_4) -10.6$ with the correlation coefficient 81% and 90% respectively.

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العلاقة بين معامل بوند والخواص الميكانيكية لبعض الخامات بالمملكة العربية السعودية

عادة ما تتحدد طاقة تكسير وطحن الخامات في صناعة تجهيز الخامات بمؤشر بوند لحساب طاقة التكسير، بغض النظر عن تفاوت الخواص الميكانيكية للصخور. على الرغم من أنه بذلت عدة محاولات للحصول على طاقة تكسير وطحن الخامات استناداً إلى النهج النظري واعطت نتائج مؤشرة ، الا انه لمن المفيد دراسة هذه العلاقة على أساس المفهوم الفيزيائى. في هذا البحث ، تمت دراسة بعض النماذج من الخامات السعودية مثل البوكسيت، كاولينيت، جرانوديوريت، ماجنتيت، الجرانيت، فيلسبار والكوارتز حيث تم قياس اهم الخواص الميكانيكية لها مثل الصلابة، البرى، قوة تحمل الضغط ومعامل المرونة. بالاضافة لحساب معامل بوند لحساب طاقة التكسير لهذه العينات.

وقد أظهرت النتائج ان معامل بوند لحساب طاقة التكسير للعينات تمت دراستها يتراوح من 10.8 طن/ كيلووات ساعة (لخام البوكسيت حيث معدل البرى عالي القيمة وقوة تحمله للضغط منخفض) إلى 20.4 طن/ كيلووات ساعة (الجرانيت حيث مقاومته للبرى مرتفعة وقوة تحمله للضغط عالية بالاضافة لارتفاع معامل مرونته).