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Research Article

Comparison of Rock Grindability and Machine Energy Consumption Based on the Strength, Drillability, and Petrographic Characteristics of Igneous Rocks

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ABSTRACT

In the mining sector, grinding operations play a significant role in terms of energy consumption. The success of increasing efficiency in grinding operations is expressed by a decrease in energy consumption. The aim of a grinding operation is to minimize the energy expended per ton of material ground while maximizing the amount of material ground to an appropriate size. The purpose of this study is to indirectly estimate the energy consumption of mechanized excavation machines used or potentially used in mining activities and the grindability of rocks based on the petrography, strength, and drillability of rocks. In this context, the drillability values of 7 different rocks of igneous origin were determined using the drilling rate index. Uniaxial compressive strength tests were conducted to determine the strengths of the rocks. Petrographically, the rock strenght coefficients were determined. Energy values and rock grindabilities were calculated using empirical relationships based on the results obtained from the experiments. Significant relationships were found between the parameters as a result of the experimental studies.

1. Introduction

Mechanized excavation systems play an important role in enabling excavation operations to be carried out effectively, rapidly, and economically in surface and underground structures where mining, construction, and similar activities are conducted. These systems efficiently perform excavation operations, resulting in time and resource savings. Particularly in large cities, mechanized excavation systems provide solutions that meet the requirements of modern life for infrastructure projects, utilization of underground resources, and other industrial activities.

In the context of underground mining activities, new methods that can be used in the selection of mechanized excavation machines (such as roadheader machines, electro-hydraulic drills, etc.) for more economical excavation of tunnels and in performance prediction analyses are being researched from past to present to provide insights into machine energy consumption. One of the parameters that need to be considered in studies investigating these methods is the grinding process.

Grinding operations play a significant role in terms of energy consumption in the mining sector. The success of increasing efficiency in grinding operations is expressed by a decrease in energy consumption. The aim of a grinding operation is to minimize the energy expended per ton of material ground while maximizing the amount of material ground to an appropriate size.

The depletion of high-grade ore deposits to a large extent in modern times has directed the mining industry towards low-grade but large-reserve ore deposits. This transition has particularly increased the importance of the grinding process, mainly due to particle liberation. Grinding is a critical step for breaking down the ore into suitable sizes, and energy consumption is a significant concern in this process.

Preventing the production of excessively fine material in grinding operations can both increase costs and affect the desired product quality. Therefore, knowing the particle size distribution of the ground product is a critical factor to ensure control of the process. This information plays an important role in optimizing production processes and achieving energy savings.

From the past to the present, numerous researchers have conducted studies on grindability. The majority of these studies have focused on the grindability of coal, while the number of studies investigating the grindability of other rocks is limited. What sets this study apart from others is the determination of the energy consumption of mechanized excavation machines that can be used in mining activities and the grindability of rocks through empirical relationships. Additionally, the relationship between the petrographic characteristics of rocks and their grindability will be examined for the first time in this context.

In studies investigating grindability, the Bond Work Index (BWI) test method is predominantly highlighted. Due to the lengthy and laborious nature of this test for determining the grindability of materials, many researchers have proposed methods to simplify the process. The Hardgrove Grindability Index (HGI) test is more commonly preferred due to its simplicity and ease of implementation [1, 2, 3, 4, 5] found significant correlations between rock brittleness (S_{20}), a parameter of the drilling rate index (DRI) test, which is the most commonly used method for determining the rock drillability value, and the Bond Work Index. In recent years, some researchers have utilized the Hardgrove Grindability Index (HGI) as a simple and practical alternative for determining rock grindability and Bond parameters. investigated relatively fast alternative methods for determining the [6] Bond Work Index for brittle materials using a universal Hardgrove mill. [7], in their study on sodium feldspar samples, found a very high correlation ($R^2 = 0.99$) between the BWI values measured in the laboratory and the BWI values they calculated. [8], in their studies on the Zonguldak Coal Basin, utilized the HGI test to determine the grindability of coal samples and found a strong positive relationship between the HGI properties of the coals and their uniaxial compressive strength (R^2=0.84). Additionally, the same study identified a decreasing linear relationship between the Shore hardness index and HGI (R^2=0.83). The researchers also developed a strength-grindability classification for the coals of the Zonguldak Basin. [9] investigated the relationships between Bond Work Index and rock parameters using four different limestone and two different chromite samples in their study. They determined the Bond Work Index values and mechanical strength values of the rocks. According to the results they obtained, uniaxial compressive strength (UCS) values showed the highest correlations with the Bond Work Index. In their study on rocks, [10] obtained a strong relationship between the Hardgrove Grindability Index calculated Bond Work Index values and the experimental Bond Work Index values they obtained from their experimental studies. The researchers demonstrated that the grindability of rocks could be easily determined using the practical experimental method of the Hardgrove Grindability Index. [11] examined the relationships between the Bond Work Index, abrasiveness of rocks, and uniaxial compressive strength, and found a significant relationship between the Bond Work Index and uniaxial compressive strength. [12] investigated the relationship between uniaxial compressive strength, petrographic characteristics, and the Bond Work Index in the grinding of gold ores with different mineralogical properties and obtained significant results. In their study, [13] conducted Schmidt hardness, indirect tensile strength, uniaxial compressive strength, and point load strength index tests, and attempted to predict Bond Work Index values using the results obtained from these tests in artificial neural networks method. In their study, [14] compared the results obtained from Bond Work Index with rock mechanics parameters and found significant correlations. They observed meaningful relationships between the specific energy (SE) values obtained from cutting tests and the energy values obtained from the Bond Work Index test. By emphasizing the similarities between cutting and grinding mechanisms of rocks, they highlighted the importance of significant relationships between rock mechanics parameters and the Bond Work Index.

Based on this information, experimental studies have been conducted in the laboratory.

2. Materials and Methods

Experiments were conducted on samples of 7 different types of igneous rocks prepared according to appropriate standards, as illustrated in Figure 1. The strength values of the rocks were determined by uniaxial compressive strength tests. The method recommended by [15] for uniaxial compressive strength testing was followed. The press used in the experiments is shown in Figure 2.

Figure 1. Samples used in uniaxial compressive strength testing.

Figure 2. Uniaxial compressive strength testing apparatus.

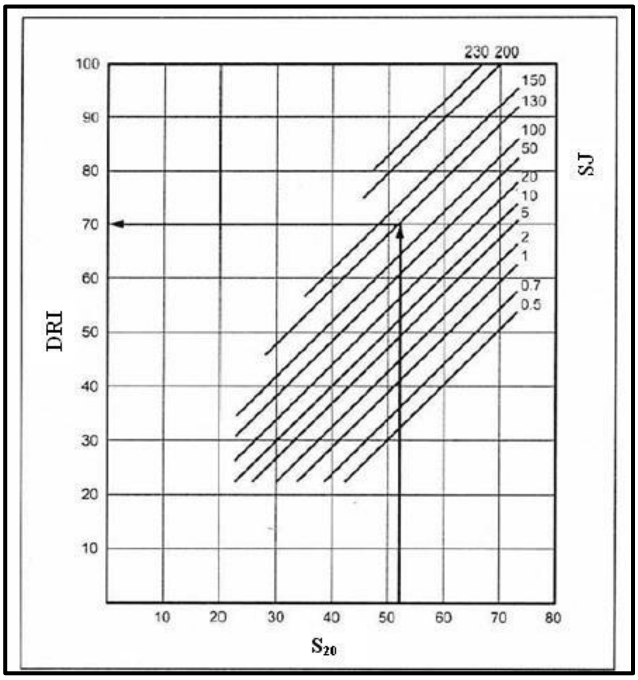

Figure 3. Diagram used for evaluating DRI [16].

The testing equipment used in the delineation experiments is shown in Figures 4 and 5.

Figure 4. Fracture test apparatus.

Figure 5. Sievers miniature drilling rig.

The cementation coefficients according to [17] were determined based on the rock's cement type (Table 1). Additionally, the cementation coefficients were multiplied by the cementation degrees determined by petrographic analysis to determine the Rock Strength Coefficient (RSC).

The RSC parameter was obtained by multiplying the cementation coefficient parameters proposed by [17] for rocks with the degree of cementation. The cementation degrees of the rocks are provided in Table 2. The higher RSC values of the M1 and M2 samples compared to the other samples are attributed to the higher quartz content in granitic rock types. In other samples, the RSC values are lower compared to granites due to the higher feldspar content. This is because the hardness strength of quartz mineral is greater than that of feldspar mineral. A high RSC value indicates that the energy expenditure will also be higher. This is because the greater the cementation of the rock, the higher its strength, which in turn requires more energy to break the rock. [18] have conducted similar analyses for comparing excavability and petrographic properties.

Table 1. Rock cementation coefficients [17].

Cement Type	Coefficient
Uncemented rocks or more than 20% porous	1
Iron	2
Iron and clay	3
Clay	4
Clay + carbonate	5
Carbonate	6
Silt; clay or siliceous calcite	7
Siliceous silt	8
Siliceous, particulate with quartz grains	9
Silica; less than 2% porosity	10

In his study, [19] obtained significant correlations between the drilling rate index and the Hardgrove grindability index (R^2=0.75). Additionally, in the same study, a high correlation was found between the Bond work index and the Hardgrove grindability index, both of which are used to determine rock grindability and energy consumption (R^2=0.98). Using the relationships between the parameters in [18] study, the Hardgrove grindability index was calculated according to Equation (1), and the Bond work index values were calculated according to Equation (2).

$$DRI=0.2063HGI+43.329 \quad (1)$$

$$BWI=-0,1414HGI+29,382 \quad (2)$$

In his study, [20] demonstrated a high correlation between specific drilling energy (SDE) and uniaxial compressive strength for igneous rocks (R^2=0.87). Using this relationship, specific drilling energy was calculated in this study according to Equation (3). [19] examined the relationship between the specific drilling energy (SDE) of rocks and other parameters using the experimental device he developed. As a result of this study, a strong correlation was obtained between SDE and UCS

$$SDE=115UCS-7221 \quad (3)$$

In his study, [21] obtained a high correlation between the rock strength coefficient (RSC) and specific cutting energy (SCE) (R^2=0.79). The relationship obtained in the study is shown in Equation (4). Using this equation, specific cutting energy was calculated based on the rock strength coefficient. [20] examined the relationship between the specific drilling energy (SCE) of rocks and other parameters using the experimental device he developed. As a result of this study, a strong correlation was obtained between SCE and RSC.

$$SCE=0.004RSC^2-6.3423RSC+2595.9 \quad (4)$$

3. Results

Both the sampling process in the field and the laboratory experiments were conducted in accordance with the standards of the International Society for Rock Mechanics [22]. The standards followed in the experiments are presented in Table 2.

Table 2. Standards followed in the experiments.

Test	Referance	H (mm)	D (mm)	Number of Test Repetitions
UCS (σc)	ISRM (1979)	110-135	54	5
S_{20} brittleness	Dahl (2003)	Sieve size		3
SJ miniature drilling tests	Dahl (2003)	27	54	3

The obtained excavatability values are presented in Table 3.The results obtained from the experiments and equations are presented in Table 3 and Table 4.

Table 3. Experimental results.

Sample Name	DRI	UCS (MPa)	Degree of Cementation (%)	RSC
M1-Granite	52	98.47	70	630
M2-Granite	47	184.4	70	630
M3-Andezite	46	165.1	60	540
M4-Diabase	44	167.88	65	585
M5-Andesite	60	104.53	45	405
M6-Basalt	45	156.74	60	540
M7-Diorite	51	138.1	60	540

Table 4. The indirectly obtained HGI and excavability data.

Sample Name	HGI	BWI (kWh/t)	SDE (MJ/m³)	SCE (MJ/m³)
M1-Granite	42.03	23.44	4103.05	187.85
M2-Granite	17.79	26.87	9845.00	187.85
M3-Andesite	12.95	27.55	11765.50	337.46
M4-Diabase	3.25	28.92	12085.20	254.55
M5-Andesite	80.81	17.96	4799.95	683.37
M6-Basalt	8.10	28.24	10804.10	337.46
M7-Diorite	37.18	24.12	8660.50	337.46

The relationship between the Bond Work Index obtained using Equations (1) and (2), and the specific drilling energy calculated using Equation (3) is shown in Figure 6 based on the experimental results.

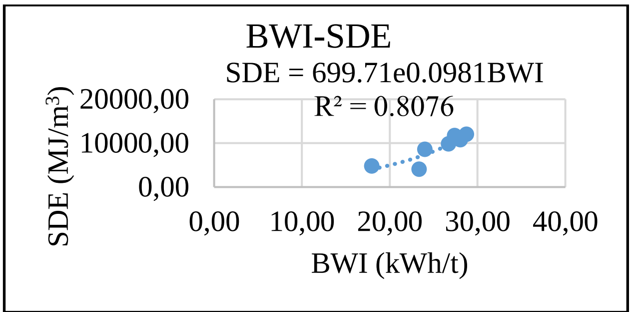

Figure 6. Relationship between BWI and SDE.

When the graph is examined, a high correlation was found between the Bond Work Index value obtained using the drilling rate index and the Hardgrove grindability index, and the specific drilling energy obtained using uniaxial compressive strength (R^2=0.81). Similar results have been reported in previous studies [14] One of the movements that occur during rock drilling is the grinding process. With this result, it will be possible in future studies to predict the energy expended during grinding using drillability values. Moreover, as seen from the graph, it is possible to calculate the energy expended during grinding using empirical relationships without performing the time-consuming Bond Work Index test.

According to the experimental results, the relationship between the Bond Work Index obtained using Equations (1) and (2), and the specific cutting energy obtained using Equation (4), is shown in Figure 7.

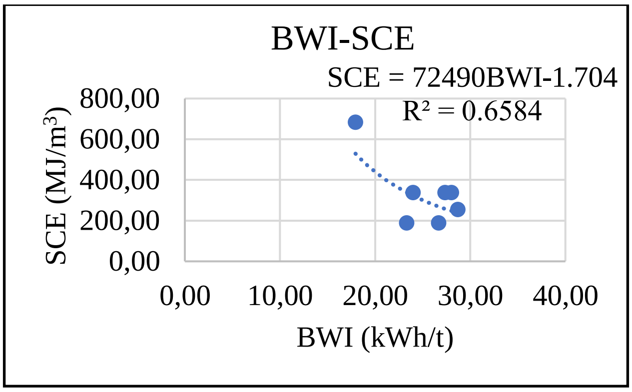

Figure 7. Relationship between BWI and SCE.

Upon examining the graph, contrary to expectations, a reverse exponential relationship between the Bond Work Index (BWI) and specific cutting energy (SCE) was obtained. Normally, an increasing relationship between the two energy values would be expected. Consequently, it is understood that using the specific cutting energy obtained through the coefficient of rock strength to predict machine energy consumption did not yield accurate results in this study.

According to the experimental results, the relationship between the specific drilling energy obtained using Equation (3) and the specific cutting energy obtained using Equation (4) is shown in Figure 8.

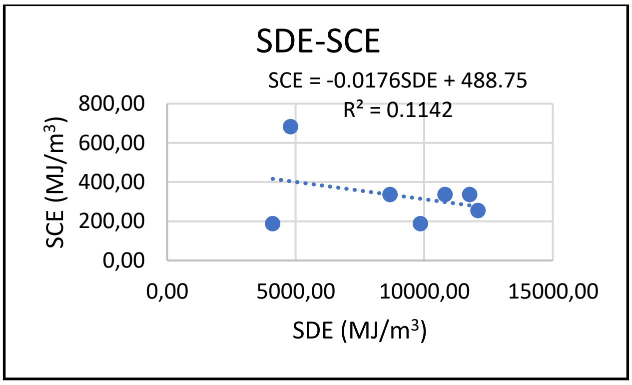

Figure 8. Relationship between SDE and SCE.

Upon examining the graph, a counterintuitive inverse relationship between specific drilling energy and specific cutting energy was observed, and no significant result was found. Consequently, it can be inferred that there is no relationship between the parameters used to obtain these two energy values in the equations, namely uniaxial compressive strength and fabric strength coefficient. It is evident that using these two parameters together to predict machine energy consumption did not yield meaningful results in this particular study.

4. Discussion

As a result of the obtained findings, a high correlation was found between the drilling rate index and the Bond Work Index (BWI) obtained using the drilling rate index and the Hardgrove grindability index (R^2=0.81). From this, it is understood that indirectly predicting machine energy consumption is possible. In future studies, it would be more logical to conduct studies where the Bond Work Index is estimated using the Hardgrove grindability index, as the Bond Work Index test is cumbersome and time-consuming. However, contrary to expectations, a reverse exponential relationship was obtained between the energy value obtained with the Bond Work Index and the specific cutting energy. It was observed that using the specific cutting energy determined by the rock strength coefficient did not yield accurate results for predicting machine energy consumption in this study. Similarly, a reverse relationship was also observed between specific drilling energy and specific cutting energy, and no significant result was found. It can be interpreted that there is no relationship between the parameters used in the equations to obtain these two energy values, namely uniaxial compressive strength and rock strength coefficient. It was found that only one out of three different comparisons yielded significant results (Figure 6). However, to obtain more reliable results, the number of samples should be increased, experiments should be conducted for other rock types (sedimentary, metamorphic), and the combined effect of all parameters (strength, drillability, petrography) on grindability should be evaluated to predict energy consumption. Additionally, the effects of different rock properties such as abrasiveness, hardness, and indirect tensile strength on grindability should be thoroughly investigated in other studies, and suitable parameters for predicting machine energy consumption should be identified [23, 24, 25, 26, 27, 28].

The observed inverse relationships between specific drilling energy and specific cutting energy, along with unexpected trends in energy metrics, warrant further investigation (Figures 7-8). Potential factors include experimental limitations, sample variability, and unexplored petrographic effects. These findings highlight the need for more comprehensive studies involving larger datasets and statistical models that include a variety of rock types.

Although the Bond Work Index (BWI) is a test method used to determine grindability, using the energy value obtained from the test to evaluate the excavability of rocks can provide preliminary insight for researchers considering future studies in this field.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared" "There is no conflict of interest with any person / institution in the article prepared"

Authors' Contributions

-Study conception and design: Aldı

-Acquisition of data: Aldı

-Analysis and interpretation of data: Aldı

-Drafting of manuscript: Güloğlu

-Critical revision: Güloğlu

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