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DETERMINATION OF THE PARAMETERS AFFECTING THE GRINDABILITY OF COAL SURROUNDING ROCKS

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Abstract

This study investigates the grindability parameters of coal surrounding rocks (sandstone and siltstone) from the Zonguldak Basin using Hardgrove Grindability Index (HGI) and Bond Work Index (BWI) tests. Eleven different rock samples were tested to determine the relationships between grindability and mechanical properties including uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), Cerchar Abrasiveness Index (CAI), Equotip hardness (ESD), and drillability parameters. Strong correlations were found between HGI and UCS (R^2=0.99), HGI and BWI (R^2=0.92) and HGI and drilling rate index (R^2=0.90). The results show that mechanical properties significantly affect the grindability of rock, with harder and more abrasive rock requiring higher grinding energy. This research provides the first comprehensive analysis of the grindability behavior of rocks in the coal environment and creates predictive models that allow mining engineers to estimate energy consumption and equipment requirements without conducting time-consuming grindability tests. The developed correlations provide direct cost savings by enabling rapid assessment of grinding parameters at the planning stage of mining, helping to optimize energy consumption and predict equipment wear in underground coal mining.

Key words: *Hardgrove Grindability Index, Bond Work Index, Zonguldak Basin, coal surrounding rocks, rock mechanics.*

1. Introduction

The depletion of easily extractable surface ore deposits has increasingly directed the mining industry toward underground mining methods. Underground operations face significant challenges related to excavation costs, particularly during tunneling and ore processing phases. These costs encompass equipment expenses, labor requirements, technological infrastructure, and safety measures that constitute substantial portions of project budgets.

In mining operations, crushing and particularly grinding processes in the ore preparation stage are often the most expensive factors. Only a very small percentage (0.1-2%) of the energy spent in the size reduction process is used efficiently; a large portion is lost as friction, noise, and heat by the crushing and grinding equipment Ozdag (1992) [1]. Approximately half of the energy used in ore preparation plants is consumed in grinding processes Yildiz (1999) [2].

Despite the significant energy consumption and costs associated with grinding operations in coal mining, a critical gap exists in the literature regarding the grindability characteristics of coal surrounding rocks. While extensive research has focused on coal grindability, the behavior of associated sandstone and siltstone layers during grinding operations remains unexplored. This knowledge gap creates substantial challenges for mining engineers who must design efficient grinding circuits and predict equipment performance without reliable predictive models for these materials.

The majority of studies in the literature to date have focused on the grindability of coal. In recent years, grindability indices have also begun to be applied to other types of rocks. However, no study has been conducted

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on the grindability of coal surrounding rocks in this context. The critical importance of this research stems from the fact that during coal extraction and processing operations, significant quantities of surrounding rocks are inevitably processed along with coal, directly affecting energy consumption, equipment wear, and operational costs. Understanding the grindability characteristics of these materials is essential for optimizing mill design, predicting power requirements, and developing cost-effective processing strategies.

A previous study by Aldı (2023) [3] investigated the relationships between strength, drillability, abrasiveness properties, and grindability of Armutcuk coal surrounding rocks from the Zonguldak Basin using seven samples. The present study extends this research by examining eleven different samples with a more comprehensive approach, establishing broader predictive relationships for industrial application across the entire basin. Additionally, the mechanical properties of the rocks in the Armutcuk region, such as strength and hardness, are lower compared to other areas of the Zonguldak Basin, leading to different outcomes in terms of energy consumption and rock grindability.

This study addresses several fundamental questions that have remained unanswered in mining engineering practice: (1) Can simplified grindability tests be used to predict the grinding behavior of coal surrounding rocks? (2) Which mechanical properties serve as the most reliable predictors of grinding energy requirements? (3) How can mining operations optimize equipment selection and energy consumption based on readily available rock property data? By answering these questions, this research fills a critical void in the literature and provides practical solutions for the mining industry.

Ozkahraman (2005) [4], identified very high correlation coefficients between the rock fragility (S_{20}), a key parameter of the drillability index (DRI) test commonly used for determining rock drillability and Bond grindability parameters (BWI and Gbg).

Ozer and Cabuk (2007) [5], in their study using four different limestone and two different chromite samples, investigated the relationships between Bond Work Index (BWI) and rock parameters. Based on the results obtained by determining the Bond Work Index and mechanical strength values of the samples, they stated that Shore hardness, point load index, and uniaxial compressive strength values provided the strongest relationships with the Bond Work Index.

Aras et al. (2020) [6] used rock properties such as Schmidt hardness, uniaxial compressive strength, indirect tensile strength, point load strength index, ultrasonic velocity, and density in artificial neural networks to predict Bond Work Index (BWI) values.

In recent years, some researchers have utilized the Hardgrove Grindability Index (HGI) test as a simple and practical alternative for determining rock grindability and Bond parameters. Bond (1954, 1961) [7,8] examined the relationships between HGI and Bond in his studies on coals. Hease et al (1975) [9] and McIntyre and Plitt (1980) [10] separately adapted Bond's approach, developed for coal, to limestone and other brittle materials. A similar model was proposed for bauxite types by Csoke et al. (2004) [11]. Hower et al. (1992) [12] demonstrated the relationship between HGI and Bond for carbonate-origin rocks.

Musci et al. (2008) [13] explored relatively fast alternative methods for determining Bond Work Index using a universal Hardgrove mill for brittle materials. The HGI test method, while widely used for analyzing the grindability of coal samples, has also gained importance in recent years as a practical and easily applicable method for determining the grindability of rock samples Swain and Rao (2009), Abdelhaffez (2012) [14,15].

Swain and Rao (2009) [14], in their study on rocks, found a very strong linear relationship (R^2=0.99) between the Bond Work Index (BWI) values they calculated using HGI values and the BWI values obtained from experimental studies. These researchers demonstrated that the grindability of rocks can be easily determined using.

Kahraman et al. (2019) [16] investigated the grindability of granite rocks based on their physico-mechanical and mineralogical properties.

Rattanakawin and Tin (2019) [17] found a strong correlation (R^2=0.99) between the laboratory-measured and calculated Bond Work Index values of sodium feldspar samples.

Abdelhaffez (2020) [18] investigated the relationships between mechanical and petrographic properties and the Bond Work Index in gold ores with different mineralogical compositions.

Lawson (2020) [19] emphasized that low HGI (Hardgrove Grindability Index) values in coals are associated with low carbon content.

Park and Kim (2020) [20] identified relationships between tensile strength, Bond Work Index parameters, and drilling rates.

Nikolić and Trumić (2021) [21], in their Bond Work Index (BWI) tests conducted on soft and medium-hard rock samples, noted that the amount of energy consumed varied depending on rock hardness.

Bhuiyan et al. (2022) [22] demonstrated that Bond Work Index (BWI) values can be estimated using Equotip Leeb Hardness (ELT) and point load strength index tests.

In a study on limestone, it was concluded that the mineralogical properties of the rock significantly influence its grindability. Additionally, among the Bond Work Index (BWI) test parameters, the Bond ball mill grindability value (Gbg) could be estimated using the Hardgrove Grindability Index (HGI) Deniz (2022) [23].

Pyshyev et al. (2023) [24] conducted a study to determine the grindability of 14 different coals using the Protodyakonov and Hardgrove methods. They found an inverse relationship between Protodyakonov's strength coefficient and HGI (Hardgrove Grindability Index), which was expressed as a second-degree polynomial. Additionally, they stated that these results could be used to estimate coal grindability and calculate the required energy for grinding operations.

HGI is a practical test method. Especially when reviewing the studies conducted, it can be seen that the HGI test method has become increasingly important and offers ease of application in determining rock grindability.

Sakiz (2021a) [25], in his study on 14 different rock samples, demonstrated that the drillability index (DRI) parameter could be practically predicted using the HGI property of the rock. However, he emphasized that the number of rocks studied should be increased, and rocks should also be evaluated based on their origin to propose a more reliable classification suggestion and prediction model. Additionally, he underlined the need to examine the precision of intervals for grindability classification.

Sakiz (2021b) [26], in his study on seven different andesite rocks, examined the relationship between abrasiveness and grindability and found that the rock's wear characteristics could be easily determined using the Hardgrove Grindability Index (HGI) when considering three widely used wear test methods (Cerchar, Norwegian, Schizamek). However, he stated that the predictive models developed to determine rock abrasiveness based on the Hardgrove Grindability Index were limited by the wear value ranges of the rocks examined. He emphasized that to develop more reliable predictive models, the number of rocks studied should be increased, and different rock origins should be considered.

The novelty of this research lies in its comprehensive approach to characterizing coal surrounding rocks through multiple mechanical property assessments and establishing robust predictive relationships for industrial application. Unlike previous studies that focused on individual rock types or specific grindability indices, this work systematically examines the interconnections between various mechanical properties and grinding behavior, providing a holistic understanding of these materials' processing characteristics.

This study aims to determine the grindability characteristics of coal surrounding rocks in the Zonguldak Basin using the Hardgrove Grindability Index (HGI) test method and to establish the relationships between grindability and various physical and mechanical properties of these rocks. In addition, this research investigates the use of Bond Work Index (BWI) values for evaluating the energy consumption requirements in grinding operations of coal surrounding rocks, thereby providing fundamental parameters for optimizing mining equipment selection and energy efficiency in underground coal mining operations. Most importantly, this study establishes the first systematic framework for predicting grinding behavior of coal surrounding rocks using readily available mechanical property data, enabling mining engineers to make informed decisions about equipment selection, energy budgeting, and process optimization without the need for extensive laboratory testing programs.

2. Data and Methods

Experiments were conducted on 11 different sedimentary-origin sandstone and siltstone rocks collected from the Zonguldak Basin. The samples were specifically selected to represent the typical stratigraphic variations encountered in active mining operations within the basin, ensuring the practical relevance of the results for industrial applications. The samples, prepared according to the appropriate standards, are shown in Fig. 1. The strength values of the rocks were determined through uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) tests. The method proposed by ISRM (1981) [27] was followed for the uniaxial compressive strength (UCS) test ISRM (1979) [28,29], while the method suggested by ISRM (1978) [30,31] was used for the Brazilian tensile strength (BTS) test.

The drillability of the rocks was determined using S_{20} brittleness and SJ miniature drilling tests, and the drilling rate indices (DRI) were calculated using the chart shown in Fig. 2.

Figure 1 Core samples prepared in accordance with standards

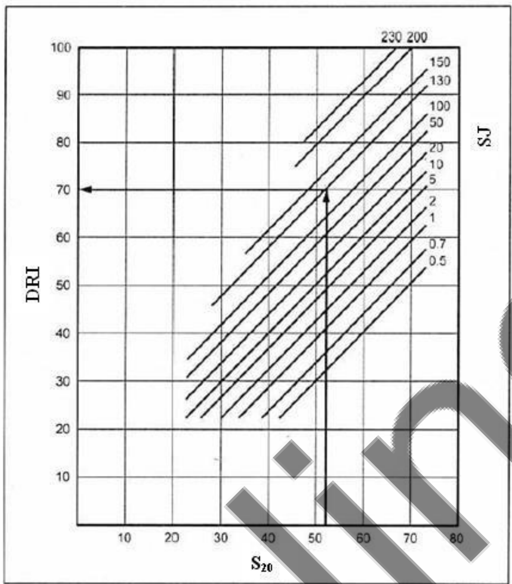

Figure 2 Diagram used for determining the DRI Dahl (2003) [32]

The Hardgrove Grindability Index (HGI) test was conducted to determine the grindability of the rocks, and the results were compared with the strength, drillability, abrasiveness, and excavability values of the rocks. First, 50 grams of rock samples with a particle size of -1180 μm +600 μm were prepared. Then, the prepared samples were ground in the HGI mill at 60 revolutions. Finally, the ground material was sieved through a 200 mesh screen, and the HGI results were calculated using Eq. (1) below ASTM (1993) [33].

$$HGI = 13 + 6.93D \tag{1}$$

Here;
HGI: Hardgrove Grindability Index,
D: The amount of rock that passed through the 200 mesh screen.

To determine the abrasiveness values of the rocks, Cerchar Abrasiveness Index (CAI) tests were conducted. The method proposed by Alber et al. (2013) [34] was taken into consideration in the experiments ISRM (2014) [35].

The Bond Work Index (BWI) can be defined as the energy consumed per ton in the grinding process required to reduce the theoretical size of a mass of ore, in which 80% passes through an infinite theoretical screen, to 100 microns. The BWI value for the ground material is determined based on the formula specified in Eq. (2). The obtained values have been used in the evaluation of the excavability of the rocks.

$$BWI = \frac{1.1*44.5}{\left((P1)^{0.23}*(Gbg)^{0.82}*\left(\frac{10}{\sqrt{P}}\right)-\left(\frac{10}{\sqrt{F}}\right)\right)} \tag{2}$$

Here;
BWI: Bond Work Index (kWh/t),
P1: screen aperture of the test (μm),
Gbg: Bond's standard ball mill grindability value (g/rev),
P: screen aperture through which 80% of the final product passes (μm),
F: screen aperture through which 80% of the fed material passes (μm).

To determine the hardness of the rocks, a highly useful and portable Equotip hardness tester, developed for metals and powered by an electronic battery, is utilized. Depending on the tip width and the applied impact energy, this device is classified into types C, D, DC, DL, E, G, and S. The D type hardness tester, which features a tungsten carbide tip with a diameter of 3 mm and is used to measure the hardness of the rocks in this study, is shown in Fig. 3. Su (2017) [36].

Another important parameter of rock properties is brittleness. Brittleness is one of the key mechanical properties of rocks and also plays a significant role in excavation mechanics. When rocks are examined from the perspective of excavation mechanics, they exhibit two types of excavation profiles: brittle and ductile. Although a precise definition of brittleness has not been established, it can generally be determined through the uniaxial compressive strength and indirect tensile strength of the rocks, and various brittleness criteria have been proposed Copur et al. 2003 [37].

Figure 3 Equotip hardness tester used in the study

The literature recognizes four fundamental brittleness criteria. B1 and B2 were proposed by Hucka and Das (1974) [38]. Altindag (2002) [39] introduced the B3 brittleness criterion in his study. Yarali and Soyer (2011) [40] discovered the B4 brittleness criterion through their research. The equations related to these criteria are presented below (Eqs 3-6).

$$B1 = \left(\frac{UCS}{BTS}\right) \tag{3}$$

$$B2 = \frac{(UCS-BTS)}{(UCS+BTS)} \tag{4}$$

$$B3 = \frac{(UCS*BTS)}{2} \tag{5}$$

$$B4 = (UCS * BTS)^{0.72} \tag{6}$$

3. Results and Analysis

The experimental database presented in this study represents the first comprehensive grindability characterization of coal surrounding rocks from the Zonguldak Basin, providing essential baseline data for industrial applications. In this experimental study, a database was prepared using the Hardgrove Grindability Index (HGI), Bond Work Index (BWI), Drilling Rate Index (DRI), Cerchar Abrasiveness Index (CAI), Uniaxial Compressive Strength (UCS), Brazilian Tensile Strength (BTS), and Equotip Hardness Index (ESD) tests. The results obtained from the experiments are presented in Table 1. The rocks used in the experiments were obtained from the Kozlu and Karadon regions of the Zonguldak Basin. The standards adhered to in the experiments and the recommended methods are shown in Table 2.

Table 1 Experimental results

Sample Name	Rock Type	HGI	BWI (kWh/t)	UCS (MPa)	BTS (MPa)	CAI	ESD	S_{20}	SJ	DRI
1	Sandstone	85.3	19.35	97.9	10.4	2.44	617	47	81	59
2	Sandstone	88.8	19.13	90.7	9.5	2.26	604	51	81	61
3	Sandstone	76.5	19.53	104.6	10.6	2.59	655	48	76	58
4	Sandstone	86.5	17.71	94.1	9.7	2.48	610	48	79	59
5	Sandstone	87.2	17.14	91.4	9.6	2.37	600	49	81	60
6	Siltstone	100.3	15.47	67.65	6.2	0.84	524	54	85	65
7	Sandstone	69.1	22.39	125.6	13.1	3.03	629	48	75	58
8	Sandstone	65	21.43	126.9	13.5	2.87	672	47	76	57
9	Siltstone	112.8	13.75	52.5	9.6	1.32	556	57	88	68
10	Siltstone	112.1	14.55	54.8	9.8	1.38	564	58	85	67
11	Sandstone	75.6	21.76	110.4	12.8	2.25	600	50	77	60

The practical significance of these correlations extends beyond academic interest, as they enable mining engineers to estimate grinding energy requirements and predict equipment performance using standard rock mechanics tests that are routinely performed during mine development phases. A simple regression analysis was employed to investigate the relationships between variables, as detailed in Table 3. The correlation matrix between parameters is presented in Table 4.

Table 2 Recommended methods in experiments

Experiment	Reference	H (mm)	D (mm)	Number of Repeats
Uniaxial Compressive Strength (UCS)	[27,28]	108	54	5
Brazilian Tensile Strength (BTS)	[29,30]	27	54	10
Cerchar Abrasivity Index (CAI)	[34]	27	54	5-7
Brittleness Test (S_{20})	[31]	Sieve size		3
Sievers Miniature Drillability Test (SJ)	[31]	27	54	5-7
Equotip Hardness Index (ESD)	[35]	27	54	22
Hardgrove Grindability Index (HGI)	[32]	Sieve size		3
Bond Work Index (BWI)	[7]	Sieve size		3-10

Table 3 Regression equations derived from experimental relationships

Relationship	Equation	R^2
HGI and BWI	$HGI = 1744.6BWI^{-1.039}$	0.92
HGI and UCS	HGI = -0.6234UCS+144.81	0.99
HGI and BTS	HGI = -5.5254BTS+144.87	0.52
HGI and CAI	HGI = -20.226CAI+131.02	0.77
HGI and ESD	HGI = -0.3136ESD+276.26	0.72
HGI and S_{20}	$HGI = 187.63\ln(S_{20})-648.7$	0.80
HGI and SJ	HGI = 3.5723SJ-199.88	0.92
HGI and DRI	$HGI = 247.64\ln(DRI)-930.77$	0.90
HGI and B3	$HGI = 126.99e^{-8E-04B3}$	0.89
HGI and B4	$HGI = 146.48e^{-0.004B4}$	0.90

Table 4 Correlation matrix for key parameters

	HGI	BWI	UCS	BTS	CAI	ESD	S_{20}	SJ	DRI
HGI	1								
BWI	-0.95	1							
UCS	-0.99	0.97	1						
BTS	-0.72	0.78	0.76	1					
CAI	-0.88	0.84	0.90	0.77	1				
ESD	-0.85	0.77	0.85	0.76	0.93	1			
S_{20}	0.90	-0.81	-0.89	-0.50	-0.87	-0.81	1		
SJ	0.96	-0.93	-0.96	-0.74	-0.89	-0.85	0.84	1	
DRI	0.95	-0.87	-0.94	-0.60	-0.92	-0.87	0.98	0.93	1

The relationship between the Hardgrove Grindability Index (HGI), which is used to evaluate the grindability of rocks, and the Bond Work Index (BWI), used to evaluate the grinding efficiency and to calculate the required grinding power, has been examined (Fig. 4). Upon reviewing the graph, a high negative exponential relationship between the two parameters has been observed. It is understood that the easier it is to grind the rocks, the less energy is required for grinding. Based on this, it can be concluded that the energy values obtained from the Bond Work Index (BWI) tests can be utilized in future studies for evaluating the excavability of coal surrounding rocks in the Zonguldak Basin.

This HGI-BWI relationship (R^2=0.92) provides a practical tool for mining operations to estimate grinding energy requirements without conducting time-consuming

Bond Work Index tests. The relationship can be expressed as: BWI = 1744.6 × $HGI^{-1.039}$, enabling rapid energy consumption predictions during process design phases. For typical HGI values observed in this study (65-113), the predicted BWI values range from 13.75-22.39 kWh/t, which directly translates to operational costs and equipment sizing requirements.

Similar results have been obtained in previous studies. The observed HGI-BWI relationship (R^2=0.906) compares favorably with previous studies. Swain and Rao (2009) [13] reported R^2=0.99 for laterized rocks, while Rattanakawin and Tin (2019) [16] found R^2=0.99 for sodium feldspar. The slightly lower correlation in this study may reflect the heterogeneous nature of sedimentary coal surrounding rocks compared to more uniform materials studied previously. The difference and novelty of the obtained results compared to previous similar studies is that, for the first time in this context, the relationship between the Hardgrove grindability index (HGI) and Bond Work Index (BWI) has been investigated for coal surrounding rocks (sandstone and siltstone) from the Zonguldak Basin, establishing predictive models specifically applicable to Turkish coal mining operations.

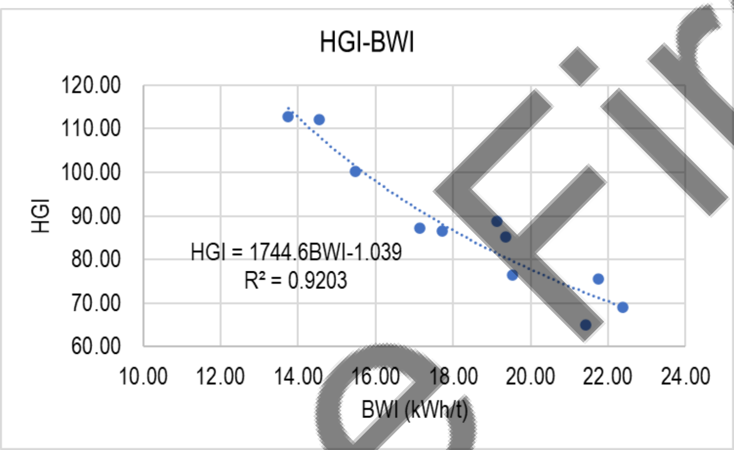

Figure 4 Relationship between HGI and BWI

The relationships between rock grindability and strength tests (UCS, BTS) have been examined (Figs. 5-6). Upon analyzing the graphs, a significant relationship was found between the uniaxial compressive strength (UCS) of the rocks and their grindability (HGI). In contrast, relatively lower relationships were observed between grindability (HGI) and indirect tensile strength (BTS). The results indicate that as the strength of the rocks increases, it becomes more difficult to grind the rock. The coal surrounding rocks of the Zonguldak Basin can be found in different stratigraphic series, and variations among these series may lead to differences in rock strength. Since all the rocks used in this study belong to the Westphalian series, the high correlation observed between the strength values and grindability of the rocks was as expected. Similar results have been reported in previous studies. In their study, Sakiz (2021a) [24] conducted experiments on 14 different rock samples and revealed a strong correlation (R^2=0.93) between the uniaxial compressive strength of the rocks and their HGI (Hardgrove Grindability Index).

In this study, the relationships between the grindability and abrasiveness of the rocks were examined (Fig. 7). The graph shows a negatively linear relationship between the grindability of the rocks and their abrasiveness. It can be understood from the graph that the higher the abrasiveness of the rocks, the more difficult it is to grind them. In his study, Sakiz (2021b) [25] found similar results. Sakiz (2021b) [25] obtained a high correlation (R^2=0.92) between HGI and CAI in their study involving seven different andesite samples. In contrast, the present study focuses on sedimentary rocks rather than igneous rock samples. These results demonstrate that the relationship between HGI and CAI exhibits strong correlations regardless of rock type. Grindability, like the crushing process, is a method used to reduce the size of a material. In the CAI test, fragments are detached from the material over a certain scratching distance, naturally resulting in size reduction. Both experimental methods involve similar failure mechanisms for the rock. Therefore, as expected, the correlation between these two parameters was found to be high.

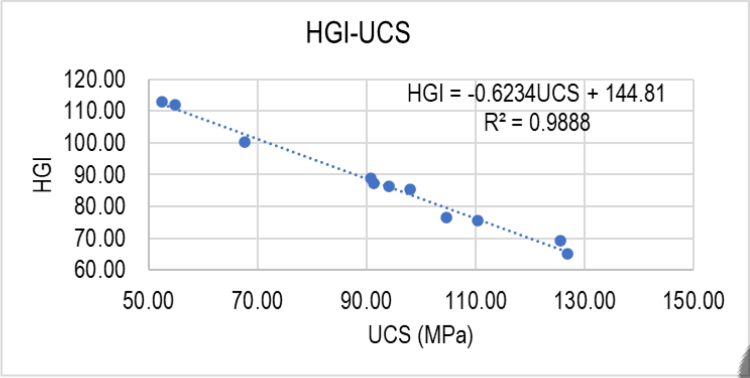

Figure 5 The relationship between HGI and UCS.

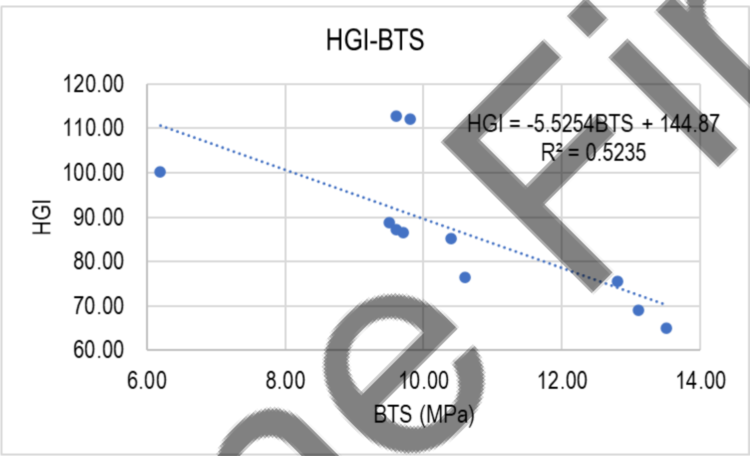

Figure 6 The relationship between HGI and BTS

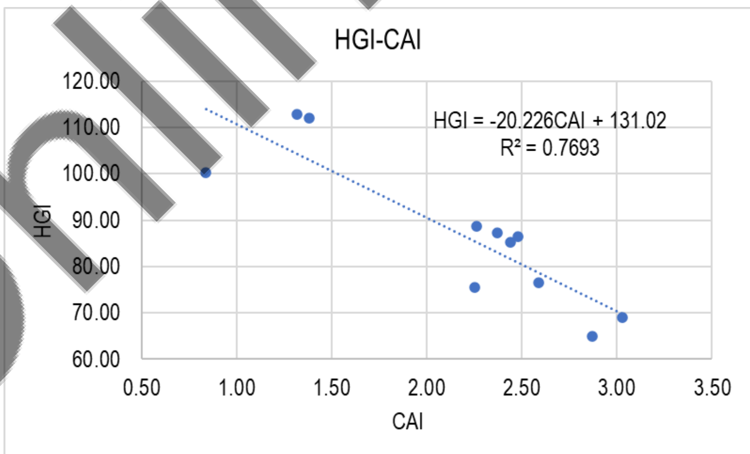

Figure 7 Relationship between HGI and CAI

The relationships between the grindability and hardness of rocks have been examined (Fig. 8). Upon examining the graph, a strong negative linear relationship between the grindability and hardness of the rocks has been found. The higher the hardness of the rock, the more difficult it is to grind. Similar results have been reported in previous studies [4,5]. The rocks used in the study are part of the Westphalian series of the Zonguldak Basin. Additionally, it is considered that the mineralogical properties of the rocks such as texture, type of cement, degree of cementation, and the size of abrasive minerals are significant factors contributing to the results obtained in this study.

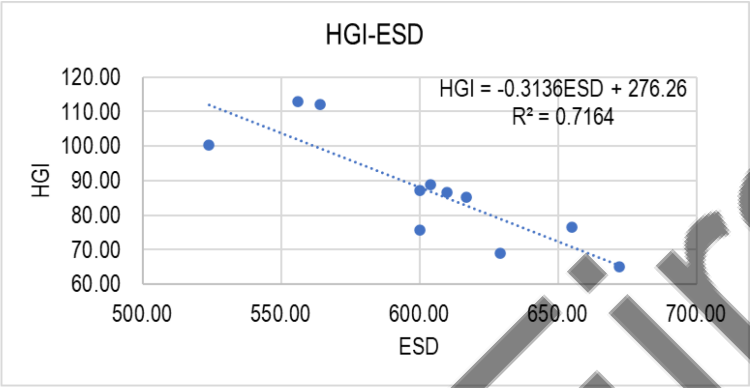

Figure 8 Relationship between HGI and ESD

The relationships between the grindability of rocks and the two testing methods used to determine the drilling rate index (DRI) and drillability (S_{20}, SJ) have been examined. Looking at the results between the S_{20}, which is an indicator of percussion drilling, and HGI, there is a linear increasing high relationship between HGI and S_{20} (Fig. 9). The higher the fragility of the rock (S_{20}), the easier it is to grind the rock. A similar high relationship has also been identified between SJ, which indicates rotary drilling, and HGI (Fig. 10). A logarithmic high relationship has been obtained between the grindability of the rocks and the drilling rate index (DRI) (Fig. 11). As unexpected, the easier it is to drill the rock, the easier it is to grind it as well. Similar results have been obtained in previous studies [4,5,24]. During the drilling process, the failure mechanism of the rock caused by the drill bit occurs through shearing, fragmentation, and grinding. Grinding, which takes place during drilling, can be defined as the process by which numerous cutting elements on the drill bit break the rock into smaller particles. The particles detached from the rock surface by the drill bits contribute to the grinding of the material. Therefore, the grinding process lies at the core of the rock failure mechanism during drilling operations. Moreover, since the failure mechanism during drilling occurs in the form of grinding, it is particularly important to investigate the grindability properties of rocks. From this perspective, the significance of grinding in excavation mechanics becomes more clearly evident through the results obtained.

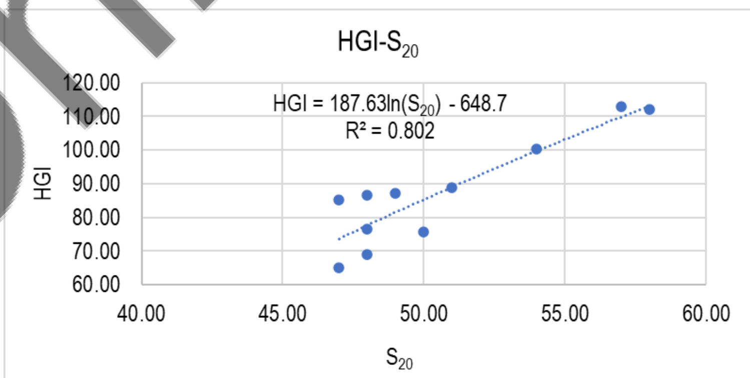

Figure 9 Relationship between HGI and S_{20}

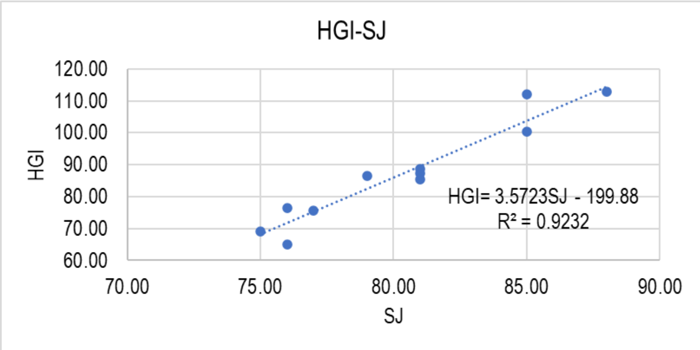

Figure 10 Relationship between HGI and SJ

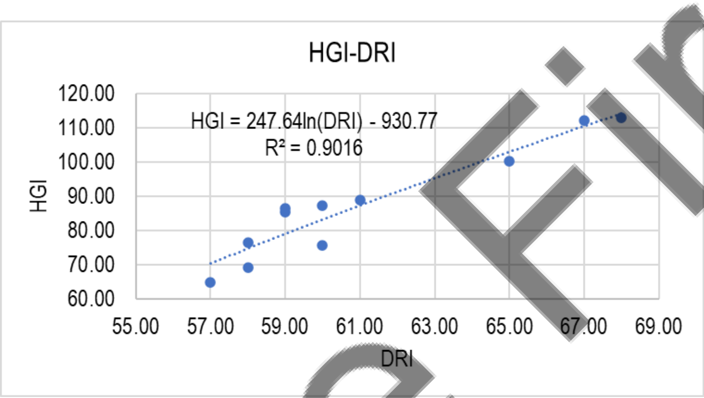

Figure 11 Relationship between HGI and DRI

Finally, the relationships between the grindability of rocks and their brittleness have been examined (Figs. 12-13). No significant relationships were found between the brittleness measures B1 and B2 used to determine the brittleness of the rocks and their grindability (HGI) (R^2=0.48-0.52). However, negative high relationships were obtained between the brittleness values B3 and B4 and HGI. The higher the brittleness characteristic of the rocks, the easier their grindability becomes. A lower brittleness value indicates that the rock is more brittle, while a higher brittleness value suggests that the rock is less brittle. Based on the results, it is observed that the siltstone samples are more brittle compared to the sandstone samples.

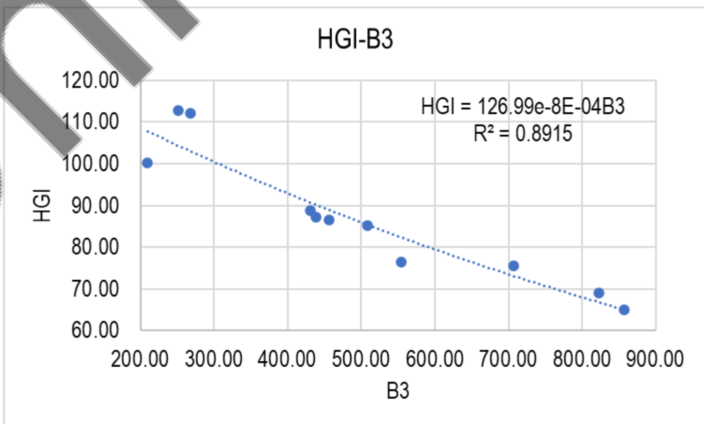

Figure 12 Relationship between HGI and B3

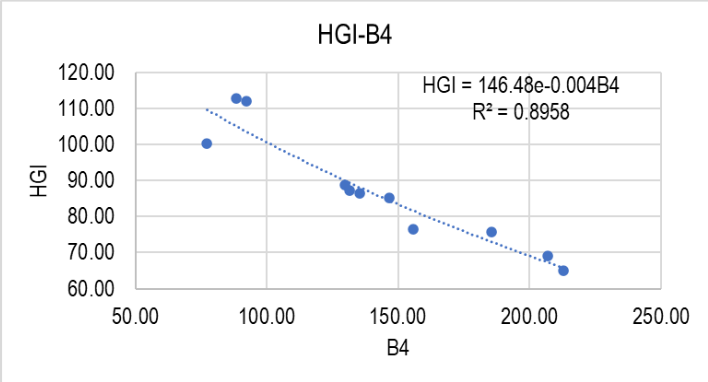

Figure 13 Relationship between HGI and B4

The exceptionally strong correlation between HGI and UCS (R^2=0.99) demonstrates that uniaxial compressive strength serves as the primary controlling factor for grindability in the studied coal surrounding rocks. This relationship enables mining engineers to estimate grindability characteristics using routine strength tests, eliminating the need for specialized grindability testing in many cases. The practical relationship HGI = -0.6234×UCS+144.81 can be directly applied in industrial settings where UCS values are readily available from geotechnical investigations.

4. Discussion

The practical significance of these correlations extends beyond academic interest, as they enable mining engineers to estimate grinding energy requirements and predict equipment performance using standard rock mechanics tests that are routinely performed during mine development phases. The relationships established in this study demonstrate several key findings that advance our understanding of coal surrounding rock behavior during grinding operations.

The strong negative exponential relationship between HGI and BWI (R^2=0.92) provides a practical tool for mining operations to estimate grinding energy requirements without conducting time-consuming Bond Work Index tests. The relationship can be expressed as: BWI = 1744.6 × $HGI^{-1.039}$, enabling rapid energy consumption predictions during process design phases. For typical HGI values observed in this study (65-113), the predicted BWI values range from 13.75-22.39 kWh/t, which directly translates to operational costs and equipment sizing requirements.

The observed HGI-BWI relationship compares favorably with previous studies. Swain and Rao (2009) [14] reported R^2=0.99 for laterized rocks, while Rattanakawin and Tin (2019) [15] found R^2=0.99 for sodium feldspar. The slightly lower correlation in this study may reflect the heterogeneous nature of sedimentary coal surrounding rocks compared to more uniform materials studied previously. Aldı (2023) [3] reported similar correlations for Armutcuk coal surrounding rocks, confirming the consistency of these relationships across different locations within the Zonguldak Basin.

The exceptionally strong correlation between HGI and UCS (R^2=0.99) demonstrates that uniaxial compressive strength serves as the primary controlling factor for grindability in the studied coal surrounding rocks. This relationship is notably stronger than the HGI-BTS correlation (R^2=0.52), indicating that compressive failure mechanisms dominate during grinding operations rather than tensile failure modes. The uniform lithological composition of the samples, all belonging to the Westphalian series, likely contributes to this consistent relationship by minimizing geological variability.

The weaker correlation with Brazilian tensile strength suggests that while tensile properties influence grindability, the grinding process in coal surrounding rocks is predominantly controlled by compressive failure mechanisms. This finding has practical implications for predicting grinding behavior, as UCS tests are more readily available in mining operations compared to specialized grindability tests.

The negative correlations between HGI and both CAI (R^2=0.77) and ESD (R^2=0.72) demonstrate that abrasiveness and hardness significantly influence grindability behavior. These relationships are particularly relevant for equipment selection and maintenance planning, as more abrasive and harder rocks will cause greater wear on grinding equipment while requiring more energy for size reduction. The correlation between abrasiveness and grindability confirms that similar rock failure mechanisms operate in both scratching (CAI test) and grinding processes.

The strong positive correlations between HGI and drillability parameters (S_{20}: R^2=0.80, DRI: R^2=0.90) reveal fundamental similarities in rock failure mechanisms during drilling and grinding operations. These relationships validate the concept that rocks exhibiting good drillability characteristics will generally demonstrate favorable grindability properties. The logarithmic relationship between HGI and DRI indicates that improvements in drillability translate to proportionally greater improvements in grindability, particularly for rocks with initially poor drilling characteristics.

The differential performance of brittleness criteria in predicting grindability provides insights into the most appropriate mechanical property combinations for characterizing coal surrounding rocks. The strong correlations observed with B3 and B4 criteria (R^2=0.89-0.90), compared to weaker relationships with B1 and B2 (R^2=0.48-0.52), indicate that brittleness formulations incorporating both UCS and BTS values are more effective predictors than simple ratio-based approaches.

The practical applications of this research for the mining industry include:

1. Equipment Selection Optimization: The established correlations enable mining engineers to select appropriate grinding equipment based on readily available rock property data, reducing the risk of under-or over-sizing equipment and associated capital expenditure inefficiencies.

2. Energy Consumption Prediction: The HGI-BWI relationship allows for accurate estimation of grinding energy requirements during feasibility studies and operational planning phases, contributing to more precise cost estimations and energy budgeting.

3. Process Design Enhancement: The strong correlations between mechanical properties and grindability provide fundamental data for optimizing grinding circuit design, including mill sizing, power requirements, and throughput predictions.

4. Equipment Maintenance Planning: The established relationships between abrasiveness (CAI) and grindability enable predictive maintenance strategies, allowing operators to anticipate equipment wear and plan maintenance schedules more effectively.

The economic impact of this research extends to multiple aspects of mining operations. By enabling accurate prediction of grinding energy requirements, mining companies can optimize their energy procurement strategies and equipment utilization rates. The ability to predict equipment wear through abrasiveness correlations allows for better inventory management and reduced unplanned downtime.

Future industrial applications should focus on:

1. Integration into Mine Planning Software: The developed correlations can be incorporated into commercially available mine planning software packages, enabling automatic energy consumption calculations and equipment selection recommendations.

2. Real-time Process Optimization: The relationships established in this study can serve as the foundation for developing real-time monitoring and control systems that adjust grinding parameters based on feed material characteristics.

3. Extension to Other Coal Basins: The methodology developed in this study should be applied to other coal-producing regions to establish basin-specific correlations and develop a comprehensive database for global application.

5. Conclusions

This study establishes the first comprehensive framework for understanding and predicting the grindability behavior of coal surrounding rocks, addressing a critical knowledge gap in mining engineering. The developed correlations provide practical tools for mining operations to optimize energy consumption, equipment selection, and process design without extensive laboratory testing programs.

Key findings of this research include:

1. Strong HGI-BWI Correlation: A robust negative exponential relationship (R^2=0.92) enables energy consumption prediction without time-consuming BWI tests.

2. UCS as Primary Predictor: The exceptional correlation between HGI and UCS (R^2=0.99) establishes uniaxial compressive strength as the dominant controlling factor for grindability.

3. Practical Predictive Models: The developed correlations allow mining engineers to estimate grindability characteristics using routine strength tests, eliminating specialized grindability testing in many cases.

4. Equipment Optimization: Relationships between abrasiveness, hardness, and grindability enable better equipment selection and maintenance planning.

5. Energy Efficiency: The established models contribute to energy consumption optimization and cost reduction in underground coal mining operations.

This research confirms and extends the findings of Aldi (2023) [3] for Armutcuk coal surrounding rocks, demonstrating the broader applicability of grindability prediction models across the Zonguldak Basin.

The consistent relationships observed across all tested samples confirm that the Westphalian series coal surrounding rocks exhibit predictable grinding behavior based on readily measurable mechanical properties. This consistency enables the development of empirical relationships for engineering applications, reducing the need for extensive grindability testing programs.

Future studies should compare similar investigations on igneous and metamorphic rocks, consider petrographic properties, examine combined parameter effects through multiple regression analysis, and increase the number of samples for more reliable results. The development of industry-specific guidelines will facilitate the transfer of academic findings to practical applications.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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ODREĐIVANJE PARAMETARA KOJI UTIČU NA MELJIVOST STENA U OKRUŽENJU UGLJENIH SLOJEVA

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Izvod

Ova studija istražuje parametre sposobnosti mlevenja stena koje okružuju ugalj (peščar i laporac) iz Zonguldak basena primenom Hardgrovog indeksa meljivosti (HGI) i Bondovog radnog indeksa (BWI). Jedanaest različitih uzoraka stena je ispitano kako bi se utvrdile veze između meljivosti i mehaničkih svojstava, uključujući jadnoaksijalnu čvrstoću na pritisak (UCS), brazilski test za čvrstoću na zatezanje (BTS), Cerchar-ov indeks abrazivnosti (CAI), Equotip test na tvrdoću (ESD) i parametre bušivosti. Uočene su snažne korelacije između HGI i UCS (R^2=0,99), HGI i BWI (R^2=0,92) kao i HGI i indeksa brzine bušenja (R^2=0,90). Rezultati pokazuju da mehaničke osobine značajno utiču na sposobnost mlevenja stena, pri čemu tvrđe i abrazivnije stene zahtevaju veću energiju za mlevenje. Ovo istraživanje predstavlja prvu sveobuhvatnu analizu ponašanja stena koje se nalaze u okruženju ugljenih slojeva u pogledu njihove meljivosti i pruža prediktivne modele koji omogućavaju rudarskim inženjerima da procene potrošnju energije i potrebnu opremu bez sprovođenja dugotrajnih testova meljivosti. Razvijene korelacije omogućavaju direktne uštede troškova kroz brzu procenu parametara mlevenja u fazi planiranja eksploatacije, doprinoseći optimizaciji potrošnje energije i predviđanju habanja opreme u podzemnoj eksploataciji uglja.

Ključne reči: *Hardgrov indeks meljivosti, Bondov radni indeks, Zonguldak basen, stene u okruženju uglja, mehanika stena.*