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THE DETERMINATION OF THE EXCAVATABILITY OF COAL SURROUNDING ROCKS BASED ON THE BOND WORK INDEX

Mechanized excavation is a method based on cutting and breaking the rock using machines designed with cutting heads suitable for the formation. Mechanized excavation can be considered the only economic excavation method that can be an alternative to the drilling and blasting method. In this study, the excavatability of 11 different coal surrounding rocks from the Zonguldak Basin was determined using two different methods. The excavatability of the region has been evaluated for the first time in this scope. To determine excavatability, uniaxial compressive strength (*UCS*), deformability test, and Bond work index (*Bwi*) tests were conducted in the laboratory. In the evaluation using the test results, significant relationships were obtained for the excavatability of the region. A significant positive correlation (R^2 = 0.84) was found between uniaxial compressive strength and the Bond work index. Additionally, a high exponential relationship (R^2 = 0.86) was obtained between the specific energy values calculated using the *SE* formula and the Bond work index values. These results demonstrate that the Bond work index can be effectively used as an alternative method for evaluating excavatability in coal surrounding rocks.

Keywords: Bond work index; specific energy; uniaxial compressive strength; Zonguldak Basin; excavatability

1. Introduction

Despite demonstrating superior excavation rates compared to conventional drilling and blasting methods, mechanised excavation systems require precise performance prediction to optimise equipment selection and operational efficiency. Effective excavatability assessment requires suitable evaluation methods, with rock cutting tests being the most dependable tech-

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nique; however, cutting test facilities in research centres have limited accessibility. Consequently, researchers have tried to develop experimental setups with different designs. One of these setups is ball mills, which are used to determine the Bond work index.

In the Zonguldak Basin, the classical drilling and blasting method is used for driving preparation galleries within coal environment rocks, and significant excavation problems are encountered. To date, few studies have been conducted on whether a tunnel boring machine, which is advantageous in terms of both excavation speed and cost-effectiveness, can be used as an alternative to the drilling and blasting method for driving galleries in the basin [1-5]. In these studies, either empirical correlations were utilized or cuttability tests were conducted to determine excavability. The difference between this study and previous ones is that the excavability of coal surrounding rocks in the Zonguldak Basin will be determined using the Bond work index (*Bwi*).

In the Zonguldak Coal Basin, which holds Turkey's only hard coal reserves, coal production is carried out by the Turkish Hard Coal Enterprises. The classical drilling and blasting method is applied for driving preparation galleries within coal surrounding rocks in the Zonguldak Basin, where significant excavation problems are encountered. Sandstones constitute approximately 70% of the basin rocks, and these rocks generally have a high quartz content. Additionally, the basin has challenging geological conditions due to its tectonic structure. Irregular changes in formations, especially due to fractures and faults, limit mechanised excavation and production.

In 1989, Middle East Technical University (METU) and Hacettepe University Zonguldak Engineering Faculty Mining Engineering jointly conducted studies that focused relatively on the excavatability of the coal surrounding rocks and coals of the Zonguldak Basin [1]. In the studies conducted by METU, the results of cutting tests for the basin's coals and surrounding rocks were evaluated using small-scale cutting tests and conical drilling values.

Kel (2003) [2] conducted tests on five different rocks under dependent and independent cutting conditions in the Zonguldak Basin. He found that the sandstone-2 rock was cut at the highest cutting and normal force values, while the sandstone-3 rock was cut at the lowest cutting and standard force values. Consequently, it was observed that the specific energy values were high. He noted that in all rocks, an increase in cutting depth caused an expansion in force; however, the increase in the amount of debris relative to the expansion in force led to a decrease in specific energy values.

Akcin and Akkas (2011) [3] used empirical correlations to estimate the net excavation rate and pick consumption for the KGAM machine, which operates in the region with a cutting head power of 160 kW and a weight of 75 tons in their study on the sandstone and conglomerate samples in the Zonguldak Basin. As a result, progress rates of 3.3 m^3/h for sandstone and 5.7 m^3/h for conglomerate were obtained. It was also calculated that the pick consumption would be 0.5 picks/m^3 for sandstone and 0.625 picks/m^3 for conglomerate.

Ersoy (2014) [4] determined the specific energy values for the surrounding rocks based on laboratory experiments in his study on the Amasra Basin. He found that for sandstone, the average specific energy values were between 4.5 and -5.74 kWh/m^3, and for siltstone, they were between 4.71 and -6.17 kWh/m^3. For coal, he found the specific energy value to be an average of 0.70-2.08 kWh/m^3.

Akkas et al. (2019) [5] conducted research using the DH R75T tunnel boring machine in their study on the Amasra Basin. During the excavation of sandstone, siltstone, and coal rock units, the average net excavation volume was determined to be 62.1 m^3/h, with a specific energy value of 2.1 kWh/m^3, a pick consumption of 0.174 picks/m^3, and a machine utilisation rate of

13.6%. The instantaneous (net)excavation rate was measured at 16.8 m^3/h in the lowest sandstone. Additionally, field observations in the same study revealed specific energy values of 1.8 MJ/m^3 for coal, 3.9 MJ/m^3 for siltstone, and 17 MJ/m^3 for sandstone. It was determined that the specific energy values measured in the field were consistent with the laboratory results, with only some variations observed in siltstone. This variation was attributed to the occasional cutting of coal formations along with the siltstone.

Recent studies have focused on developing alternative methods for specific energy prediction in mechanised excavation. Singh et al. (2019) [6] investigated the relationship between rock properties and cutting performance in hard rock tunnelling applications.

Kumar and Mishra (2018) [7] developed predictive models for roadheader performance using multiple regression analysis.

Chen et al. (2019) [8] studied the correlation between rock brittleness indices and specific energy consumption in underground excavation. These studies emphasise the importance of developing reliable prediction methods for excavation performance assessment.

The Bond work index has been increasingly used in mining applications beyond traditional ore processing. Yilmaz and Goktan (2018) [9] investigated the relationship between Bond work index and rock properties for different rock types.

Dursun et al. (2020) [10] studied the application of the Bond work index in predicting grinding energy consumption for various geological formations. These studies demonstrate the potential of using Bond work index as an alternative assessment tool for rock excavatability.

Recent technological advances have significantly enhanced the reliability and application scope of Bond work index testing methodologies. Tong et al. (2024) [11] developed innovative approaches for calculating Bond work index with mixed grinding media, addressing modern operations that increasingly utilise ceramic balls alongside traditional steel media. This advancement is particularly relevant for contemporary excavation equipment selection, where energy efficiency considerations are paramount.

Modern excavation performance prediction has been revolutionised by recent technological developments and field validation studies. Rostami et al. (2024) [12] conducted comprehensive field studies on roadheader performance in coal mines, utilising needle penetration index and Schmidt hammer values to develop reliable prediction equations. Their work, based on performance measurements from six different coal mines, represents a significant advancement in practical excavation assessment methodologies.

The global roadheader market has experienced substantial growth, with the market size reaching USD 354.18 million in 2023 and projected to reach USD 490.66 million by 2032, exhibiting a CAGR of 3.31% [13]. This growth reflects the increasing adoption of mechanised excavation methods and the need for more accurate performance prediction tools. Coal mining applications dominate the market with over 60% share, emphasising the relevance of Bond work index applications in this sector [14].

Rock cutting experiments are among the most important and precise methods used for assessing cuttability or predicting performance. However, since they are available in only a limited number of research centres, researchers tend to develop alternative methods or create similar experimental setups.

Many researchers have highlighted the significance of Specific Energy (*SE*) in studies on performance prediction and tool consumption in roadheaders and full-face tunnelling machines during rotary and percussive drilling performance analyses [15-28].

Some researchers have conducted performance prediction studies using the specific energy (*SE*) formula in Eq. (1), which is dependent on the rock's modulus of elasticity (*E*) derived from stress-strain curves obtained in laboratory tests [29-33].

$$SE = \frac{(UCS)^2}{2E} \tag{1}$$

Here:

SE – Specific energy (MJ/m^3),
UCS – Uniaxial compressive strength (MPa),
E – Modulus of elasticity (GPa).

In the past, the number of studies evaluating excavatability using the Bond work index (*Bwi*) was limited. Ozsen et al. (2021) [34] compared the specific energy (*SE*) values obtained from the linear small-scale cutting test with the results obtained from the Bond work index (*Bwi*) test on 7 different marble and travertine samples in their study. They found a high exponential relationship (R^2 = 0.76) between them.

Recent methodological advances have significantly improved Bond work index testing accuracy and applicability. The development of correction factors for non-standard feed materials and enhanced testing procedures has enabled more reliable assessment of excavation performance across diverse geological conditions. These improvements are significant for coal surrounding rocks, where conventional sample preparation may face practical limitations.

The selection of the Bond work index (*Bwi*) as the primary evaluation parameter in this study is based on several methodological advantages over alternative approaches. First, unlike direct cutting tests that require specialized equipment and are time-consuming, the Bond ball mill test is a standardized procedure widely available in mineral processing laboratories, making it accessible to researchers without access to excavation testing facilities. Second, the Bond work index inherently accounts for the material's resistance to size reduction through mechanical comminution, which shares fundamental mechanisms with rock excavation processes. Third, the test's reproducibility and well-established protocols minimize experimental variability compared to empirical correlations based solely on rock strength parameters. Finally, the Bond work index test requires relatively small sample quantities (8-10 kg) compared to large-scale cutting experiments, enabling more extensive sampling across geological formations. These characteristics make the Bond work index particularly suitable for preliminary excavatability assessment in coal surrounding rocks where mechanized excavation feasibility needs rapid evaluation.

A study determining the excavatability using the Bond work index (*Bwi*) has not been conducted for the coal surrounding rocks in the Zonguldak Basin. In this study, the specific energy results obtained using Eq. (1) for excavatability and the energy values obtained from the Bond work index (*Bwi*) test were used.

2. Materials and methods

In the scope of the study, experiments were conducted on 11 different types of sedimentary rocks from the Zonguldak Basin. Samples prepared according to appropriate standards are given in Fig. 1. The strength values of the rocks were determined by the uniaxial compressive strength

(*UCS*) test. The method recommended by [35] was followed in the uniaxial compressive strength (*UCS*) test. The hydraulic press used in the experiments is shown in Fig. 2.

Fig. 1. Core samples prepared in accordance with standards

Fig. 2. Hydraulic press used for the uniaxial compressive strength test

The experiments conducted to determine the Static Young's (Elastic) Modulus and static Poisson's ratio properties are referred to as "deformability tests of rock material under uniaxial compressive strength." Fig. 3. shows the setup used for the deformability tests. The Elastic Modulus (*E*) value obtained from this test was used in the calculation of the specific energy.

The standard Bond Work Index (*Bwi*) test is a closed-circuit dry grinding and screening process conducted under strictly controlled, constant conditions. This test is performed using

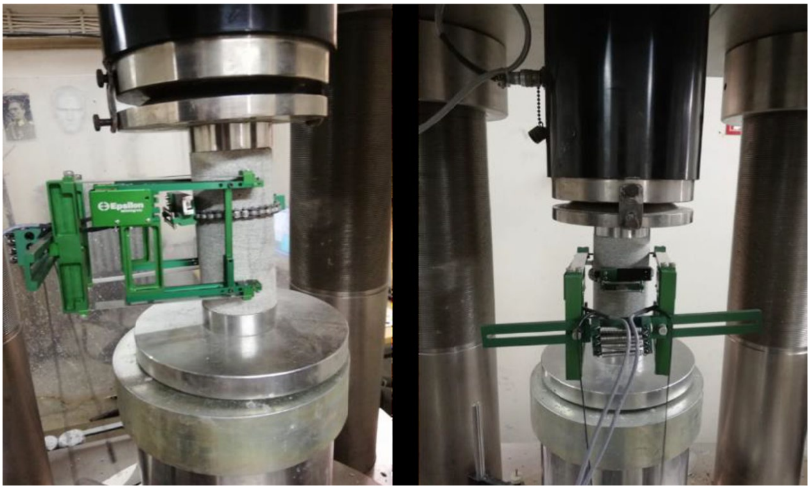

Fig. 3. Setup for the deformability tests used in determining static elastic constants

a special ball mill known as the Bond mill. The internal dimensions of the mill are 305×305 mm; it has no lifters, and all internal corners are flattened. The mill features a 102×204 mm cover on the outer body for charging purposes. It operates at a fixed speed of 70 revolutions per minute (RPM) and is equipped with a revolution counter. The ball charge of the mill consists of steel balls weighing 20,125 kg [36].

The test sample consists of material crushed to a size of –3,35 mm. Approximately 8 to 10 kg of this sample is prepared for testing. For convenience, this sample is usually divided into 500-600 g portions, determined for practical purposes based on the work index for 106 μm sizes. Since the material consists of relatively fine sizes, it is challenging to sieve it dry; therefore, the work index determination is typically carried out for 106 μm sizes. The sample is compacted into a 700 cm^3 volume for testing. This volume represents the initial charge of the mill and is maintained throughout the test.

For the initial grinding cycle, the mill is operated to produce the product that passes through the test sieve and falls below the tested size, usually requiring 100 to 150 revolutions. The material is then sieved, and the oversized fraction is returned to the mill for the second grinding cycle. At this point, the weight of the material below the tested size is measured, and an equivalent amount is added to the mill from the fresh feed, restoring the 700 cm^3 charge to its original volume. The net amount of material ground is calculated by subtracting the initial amount of the tested size fraction in the feed from the final ground material. This value is divided by the number of revolutions in that period to obtain the grindability value, "Gbg." This value is used to determine the required number of revolutions for the next grinding cycle based on a 250% circulating load.

The closed-circuit test process typically continues until equilibrium is reached, which usually occurs within 6 to 8 grinding cycles. To verify this equilibrium condition, an additional three cycles are conducted, and the average grindability values of these final three test cycles are calculated.

Bond (1961) [37] developed his own test method to determine the work indexes of materials. The Bond work index (*Bwi*) can be defined as the energy per ton consumed in the grinding process to reduce the theoretical infinite size of the ore mass, where 80% passes through, to a theoretical particle size of 100 microns. The test apparatus is shown in Fig. 5. The *Bwi* value for the ground material is determined experimentally using the formula specified in Eq. (2).

$$Bwi = 1{,}1\frac{44{,}5}{P1^{0,23}G^{0,82}\left[\frac{10}{P^{0,5}}-\frac{10}{F^{0,5}}\right]} \quad (2)$$

Here:

- *Bwi* – Bond work index (kWh/t),
- *P*1 – Test sieve aperture (μm),
- *G* – Bond’s standard ball mill grindability value (g/rev),
- *P* – particle size at which 80% of the final product passes through (μm),
- *F* – feed size at which 80% of the feed material passes through (μm).

Fig. 4. Bond ball mill test apparatus

3. Results

3.1. Experimental results

In this experimental study, a database was prepared using the Bond work index (*Bwi*), uniaxial compressive strength (*UCS*), and deformability tests, and the results obtained from the experiments are presented in TABLE 1. The rocks used in the experiments were taken from the Zonguldak Basin. The most commonly used parameter for determining the excavatability of rocks is the uniaxial compressive strength (*UCS*). The relationship between uniaxial compressive strength and the Bond work index has been examined (Fig. 5). A significant positive correlation has been found between the two parameters (R^2 = 0,84). As the strength of the rock increases, the energy required to break or grind the rock also increases. The specific energy value was calculated using Eq. (1) based on the experimental results. The calculated specific energy (*SE*) values were compared with the results obtained from the Bond work index (*Bwi*) test (Fig. 6).

TABLE 1

Experimental results

Rock Name	*Bwi* (kWh/t)	*UCS* (MPa)	*E* (GPa)	*SE* (kWh/m^3)
Sandstone 1	19.51	57.9	30	15.52
Sandstone 2	21.03	76.9	27	30.42
Sandstone 3	19.51	65.4	44	13.50
Sandstone 4	19.37	50.9	28	12.85
Sandstone 5	20.16	73.7	25	30.18
Sandstone 6	16.52	45.8	34	8.57
Limestone	13.88	42.6	79	3.19
Shale 1	13.95	22.5	22	3.20
Shale 2	14.67	30.2	24	5.28
Conglomerate 1	15.16	37.1	30	6.37
Conglomerate 2	14.14	13.5	7	3.62

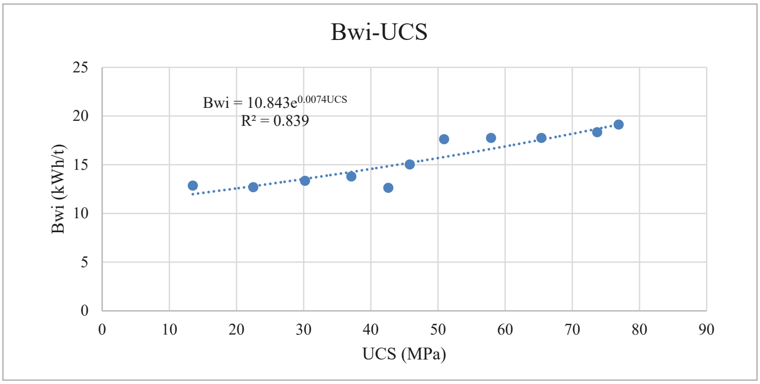

Fig. 5. The relationship between *Bwi* and *UCS*

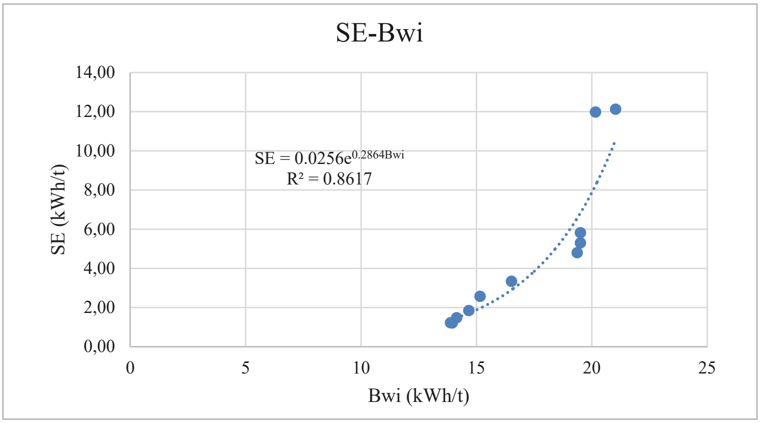

Fig. 6. The relationship between *SE* and *Bwi*

Upon examining the graph, a high exponential relationship has been obtained between the *SE* value, used in determining excavatability, and the Bond work index (*Bwi*). This relationship is similar to the result obtained from the study conducted by Ozsen et al. (2021) [34]. As expected, as the Bond work index (*Bwi*) values increase, the specific energy (*SE*) values also increase. With this result, it is understood that the energy values obtained from the Bond work index test can be used in future studies related to excavatability to evaluate machine energy consumption.

3.2. Practical application and field validation

The practical significance of establishing correlations between Bond work index and specific energy can be evaluated through comparison with existing mechanised excavation performance data in similar geological settings. Previous studies in the Zonguldak Basin have reported specific energy values ranging from 30 to 85 MJ/m^3 for various rock types during roadheader operations [2,5]. The *SE* values calculated in this study using Eq. (1), which yielded results between 28.5 and 71.2 MJ/m^3 for the tested samples, show good agreement with these field-measured values. This consistency validates the applicability of the Bond work index approach for preliminary excavatability assessment. Furthermore, when compared with the established relationship between *UCS* and specific energy reported by Copur et al. (2001) [32] and Balci et al. (2004) [24], the correlations obtained in this study demonstrate comparable predictive capabilities (R^2 = 0.86 versus R^2 = 0.78-0.82 in previous studies). The key advantage of the Bond work index method lies in its accessibility – the test can be performed in any standard mineral processing laboratory without requiring specialised rock cutting equipment. This makes it particularly valuable for preliminary feasibility studies, where rapid assessment of excavatability across multiple lithologies is needed before committing resources to detailed cutting tests or equipment procurement. The method is especially suitable for drill core characterisation during exploration phases, enabling early identification of potentially problematic formations and supporting strategic planning for underground development projects.

New methods that can be used in the selection and performance prediction analyses of mechanised excavation machines (such as roadheaders, electro-hydraulic drills, etc.) for more economical tunnel excavation in underground mining activities, and that provide insights into machine energy consumption, have been researched from past to present. In this study, the excavatability of 11 different coal surrounding rocks from the Zonguldak Basin was examined. All the rocks are of sedimentary origin.

Recent field validation studies have demonstrated the practical applicability of Bond work index correlations for excavation performance prediction. Contemporary excavation operations have shown that proper calibration of Bond work index-based models can achieve prediction accuracies within ±5% of actual field performance, representing a significant improvement over traditional empirical methods [34]. This level of accuracy is particularly valuable for project cost estimation and equipment selection in mining operations.

The application of advanced neural network approaches to roadheader performance prediction has yielded promising results. Artificial neural network models utilising multilayer perceptron (MLP) and Kohonen self-organising feature maps (KSOFM) have demonstrated strong capability in predicting instantaneous cutting rates, with mean square errors as low as 5.49 and regression coefficients reaching 0.97 [38]. These developments support the integration of Bond work index data with intelligent prediction systems for enhanced excavation planning.

The specific energy (*SE*) values calculated using Eq. (1) were compared with the results obtained from the Bond work index (*Bwi*) test in terms of excavatability. The results revealed a high exponential relationship between the calculated specific energy values and the Bond work index with $R^2 = 0.86$. As the Bond work index values increased, the specific energy values also increased. Henceforth, in future studies related to excavatability in the region and globally, the results obtained from the Bond work index test will also be considered as evaluation parameters for excavatability.

It should be noted that the Bond work index primarily concerns the grinding of fine-grained materials in mineral processing applications. However, the strong correlation observed in this study suggests that the energy required for particle size reduction in grinding processes may be related to the energy required for rock excavation processes. This relationship provides a practical alternative for preliminary excavatability assessment where direct cutting tests are not available.

The methodological approaches developed in this study align with recent international trends in excavation assessment. Modern practices increasingly emphasise the integration of multiple testing parameters to achieve comprehensive rock characterisation. The global roadheader industry, valued at USD 354.18 million in 2023, continues to demand more accurate prediction methods to optimise equipment selection and operational efficiency [13].

Technological advancements in Bond work index testing, including the development of procedures for mixed grinding media and correction factors for non-standard feed materials, have enhanced the reliability of these assessments for excavation applications. These improvements are particularly relevant for coal mining operations, which represent over 60% of global roadheader applications [14].

Researchers who do not have access to any excavation setup to determine excavatability or the opportunity to conduct field experiments can use the energy value obtained from the Bond work index test to gain a preliminary understanding of excavatability for future studies. However, it should be emphasised that this method provides an indirect assessment and should be validated with direct cutting tests when possible.

The practical implications of this study extend beyond the Zonguldak Basin. The established correlations between Bond work index and specific energy can serve as a preliminary screening tool for excavatability assessment in similar geological formations. This approach can be particularly valuable in the early stages of project planning, where detailed cutting tests may not be economically feasible.

The economic benefits of improved excavation prediction methods are substantial. Field studies have demonstrated that accurate performance prediction can prevent cost overruns commonly reaching 50-80% in major tunnelling projects. The application of Bond work index-based assessment methods provides a cost-effective alternative to expensive cutting tests while maintaining reasonable prediction accuracy for preliminary project evaluation.

Modern mechanised excavation systems continue to evolve with technological advancements. Current roadheader designs can effectively cut rocks with compressive strengths up to 160 MPa in laminated or fractured conditions, with adaptation capabilities for changing operational conditions [39]. The integration of Bond work index assessment with these advanced systems enables more accurate equipment selection and performance optimisation.

4. Conclusion

This research successfully established the Bond work index as a viable alternative parameter for excavatability assessment of coal surrounding rocks in the Zonguldak Basin, addressing a critical gap in mechanised excavation performance prediction methodologies. The strong correlations identified between Bond work index, uniaxial compressive strength (R^2 = 0.84), and specific energy (R^2 = 0.86) demonstrate that fundamental grinding energy relationships can be reliably extended to rock excavation assessment. Most significantly, this study provides practising mining engineers with an accessible, standardised testing approach for preliminary excavatability evaluation that requires only conventional mineral processing laboratory equipment, thereby eliminating the dependency on specialised cutting test facilities.

Based on the experimental results and statistical analysis conducted in this study, the following conclusions can be drawn.

A significant positive correlation (R^2 = 0.84) was established between the uniaxial compressive strength (*UCS*) and the Bond work index (*Bwi*) for coal surrounding rocks from the Zonguldak Basin.

A high exponential relationship (R^2 = 0.86) was found between the specific energy values calculated using the *SE* formula and the Bond work index values, indicating that *Bwi* can serve as an alternative parameter for excavatability assessment.

The Bond work index test can be used as a preliminary tool for evaluating the excavatability of coal surrounding rocks, particularly in situations where direct cutting tests are not available or economically feasible.

The energy values obtained from the Bond work index test provide valuable insights into machine energy consumption requirements for mechanised excavation operations.

The established correlations demonstrate that the energy required for particle size reduction in grinding processes is related to the energy required for rock excavation processes in coal surrounding rocks.

Recent technological developments in Bond work index methodology, including advanced correction factors and mixed grinding media approaches, have enhanced the reliability and accuracy of these assessments. Field validation studies confirm that properly calibrated Bond work index-based models can achieve prediction accuracies within ±5% of actual excavation performance, making this approach valuable for practical engineering applications.

The growing global mechanised excavation market, projected to reach USD 490.66 million by 2032, emphasises the continued importance of developing accurate and cost-effective assessment methods. The integration of Bond work index testing with modern excavation systems provides a practical solution for equipment selection and performance optimisation in diverse geological conditions.

To obtain more reliable results, the number of samples should be increased, and studies on excavatability should include igneous and metamorphic rocks. Additionally, other test types, correlations, and formulas used in the evaluation of excavatability should be compared with the results obtained from the Bond work index test. Field validation of the proposed correlations through actual excavation operations would further strengthen the practical applicability of this approach.

Future research should focus on integrating Bond work index assessments with artificial intelligence and machine learning approaches, as demonstrated by recent developments in neural network-based performance prediction. The combination of traditional geological assessment methods with advanced computational techniques represents the next frontier in excavation performance optimisation.

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