Journal of Geomine (2023), 1(3), 103-110
DOI: 10.22077/jgm.2024.7372.1019

# Critical Review of Scientific Studies on Rock Brittleness Index: An Overview Analysis

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Recived: 2024 Mar. 02, Revised: 2024 Apr. 04, Online Published: 2024 Apr. 09

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ABSTRACT

The role of the rock brittleness index in materials engineering and mining sciences is paramount. This article embarks on a comprehensive analysis of recent studies with the overarching goal of refining the accuracy and predictability of these indices. Various dimensions, including laboratory experiments, numerical analyses, intelligent methodologies, and analytical approaches, undergo critical scrutiny. The critiques predominantly center on methodological shortcomings in laboratory experiments, ambiguities in data interpretation, limitations of numerical methods, and inadequacies in study alignment and standardization. A meticulous exploration of these dimensions catalyzes refining existing methodologies and elevating result accuracy. While laboratory investigations into the mechanical properties of rocks hold significant importance, critiques regarding methodological inefficiencies or flaws in experiment execution are evident. Conversely, numerical studies enable the simulation of complex rock behaviors under diverse environmental conditions and loading scenarios. Nonetheless, criticisms such as ambiguities in modeling or inefficiencies in parameter selection persist. Intelligent and analytical methodologies also contribute to more precise data interpretation, yet addressing deficiencies and inefficiencies in this realm requires further attention. A thorough literature review on this subject facilitates the consideration of superior and more refined approaches in future research endeavors. Ultimately, this article endeavors to deepen the understanding of rock brittleness indices, thereby fostering advancements in the field.

KEYWORDS

Rock brittleness index, laboratory studies, numerical modeling, intelligent methods, analytical approaches, review study

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## I. INTRODUCTION

In recent decades, the fields of mining engineering and geotechnics have gained significant importance due to the continuous development of the mining industry and the expansion of underground structures (Hassanpour et al., 2021). Optimal utilization of land resources and the stability of underground structures are among the major challenges faced by mining and geotechnical engineers in today's world (Sun et al., 2018). One of the influential factors affecting the stability of underground structures as well as mining operations is the brittleness of rocks. Rock brittleness, as one of the most important mechanical properties of rocks, directly influences the strength and stability of structures as well as the efficiency of mining operations (Zhang et al., 2022). The mining industry and geotechnical engineering have played a crucial role in the creation and development of industrial and technological foundations of human societies. However, with the rapid advancement of these industries, the need for employing modern and precise methods and tools to assess and predict the mechanical properties of rocks, especially rock brittleness, has increased (Ore & Gao, 2023). This essential need for a more thorough and advanced investigation of rock brittleness through various tests and evaluation based on modeling and numerical methods, as well as artificial intelligence, leads to the enhancement of safety and efficiency in the mining and geotechnical engineering industries. In fact, rock brittleness has significant relevance to various engineering applications, as depicted in Fig. 1. The study of the brittleness index and its examination from the perspective of penetration tests provides comprehensive guidance for advancement in the tunneling industry and the selection of drilling methods. Through penetration tests, the hardness properties, compressive strength, and deformation under pressure of rocks can be understood, enabling the prediction of rock failure, stability, and relative stability between rock layers. Therefore, the study of penetration tests and the process and mechanism of failure under loads are of great importance. In 1995, Kou proposed a conventional fracture model that has shaped rock cutting tools in the rock breaking process (Kou, 1995, Eftekhari et al., 2019) (Figure 2). This model consists of various zones, including the fractured rock zone, the middle crack zone, the radial crack zone, the lateral crack zone, and the pristine zone. These conditions are essential elements for machine design and support.

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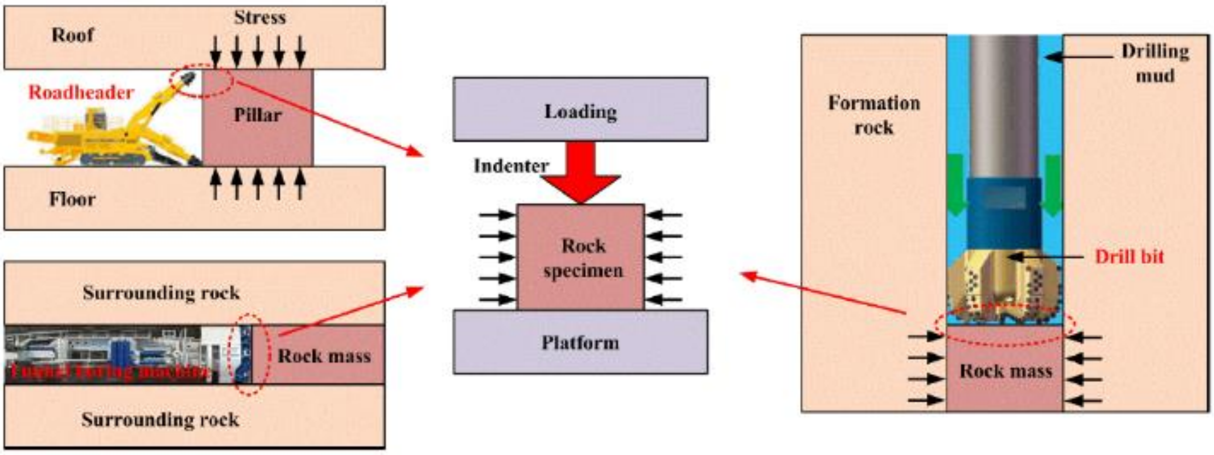


**Fig. 1.** Penetration Test in Mining Engineering, Tunnel Engineering, Oil Drilling Engineering, and Simplified Test

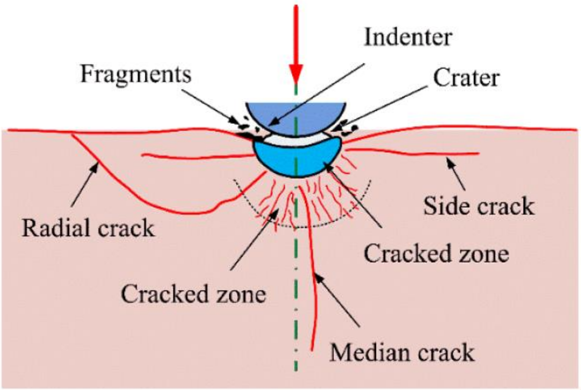


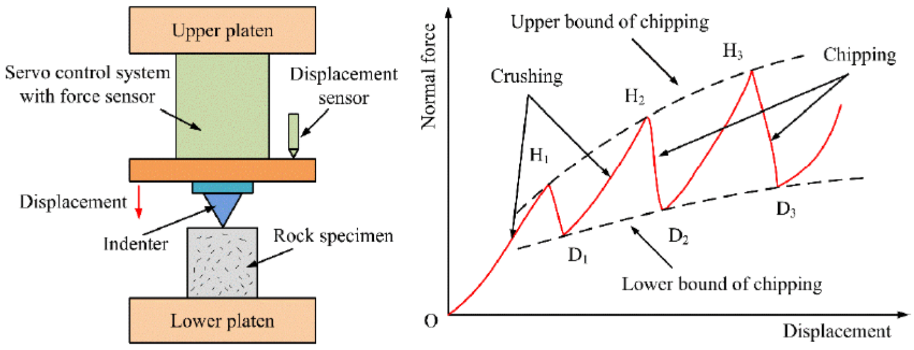
**Fig. 2.** Rock Breaking Mechanism (Kou, 1995)

Therefore, conducting penetration tests during TBM tunneling operations can increase the safety and reliability of tunnel construction while also aiding in optimizing scheduling and construction costs. The application of penetration testing is expanding further in mining engineering and oil drilling operations, primarily for obtaining the fundamental physical properties of rocks and assessing the performance of rock formations. Brittleness tests provide the capability to evaluate drilling, brittleness, and compressive resistance of rocks.

Insights derived from large-scale and small-scale experiments regarding rock properties and geological conditions play a vital role in guiding tunneling and oil drilling processes. This includes informed decision-making regarding suitable drilling machinery, optimal torque and rotation speeds, as well as determining angles and displacements for directional drilling. Additionally, it assists in formulating appropriate plans for protecting drill bits and timing their replacement, thereby ensuring the safety and quality of tunnel construction efforts. Hence, the integration of brittleness tests and consideration of force-displacement diagrams (tooth diagrams) (Fig. 3) in engineering methods are essential and highly significant. These precise geological and technical parameters provide the foundation for the success of tunneling, drilling, and overall tunnel construction activities.

They use "brittle fracture" or "brittle failure" to qualitatively describe the post-peak failure process (referred to as the brittle-ductile transition) of rock during compression testing (see Fig. 4). Brittle failure is defined as a decrease in the rock's ability to withstand load as deformation increases, while ductile behavior is characterized by increasing compressive strength with higher strain during compression testing.

It is crucial for the brittleness test to have a strong correlation with engineering performance, and due to its simple principles, it offers significant potential for practical applications on-site. Conducting in-situ brittleness tests enables engineers to acquire vital mechanical properties and rock characteristics (Meng et al., 2015). This, in turn, facilitates the optimization of design strategies and contributes to enhancing construction quality and efficiency. As mentioned, rock brittleness is considered an important component in determining the stability of underground structures and in the operation of mines and tunnels. This mechanical property of rocks has a direct impact on decision-making related to the design and implementation of underground and mining structures. Therefore, accurate evaluation of rock brittleness and understanding its performance under various conditions is of paramount importance. In this regard, given the significance of the subject, this article aims to critically examine studies conducted in the field of brittleness index from an engineering perspective.



(a) (b)

**Fig. 3.** (a) Schematic diagram of the penetration testing apparatus (b) Typical force-displacement response recorded by sensors (Kou, 1995)

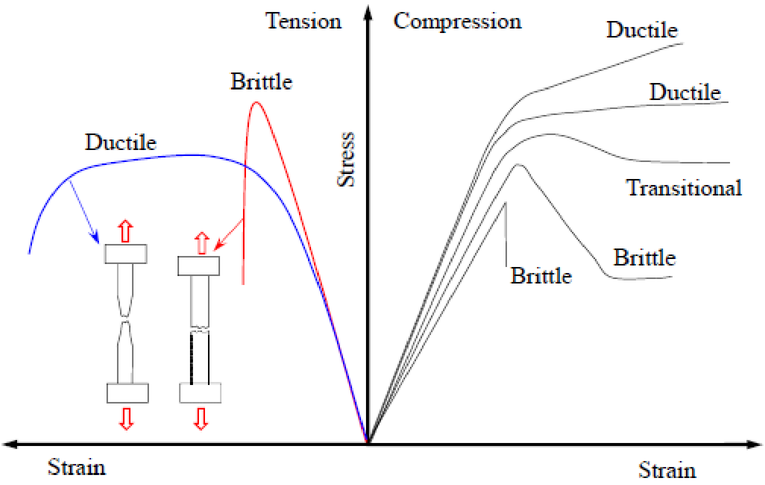


**Fig. 4.** Illustration depicting brittle and ductile behavior of materials under tension (left half) and compression (right half) loading conditions. The right segment demonstrates the brittle and ductile characteristics of trachyte at various confining pressures

## II. Studies Conducted on the Rock Brittleness Index

The literature on the rock brittleness index revolves around laboratory experiments, numerical simulations, and intelligent methods (Figure 5), and in most studies, the objective has been to estimate a new and valid index for rock brittleness.

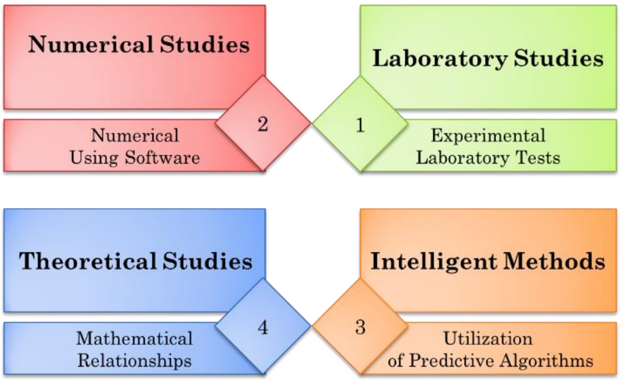
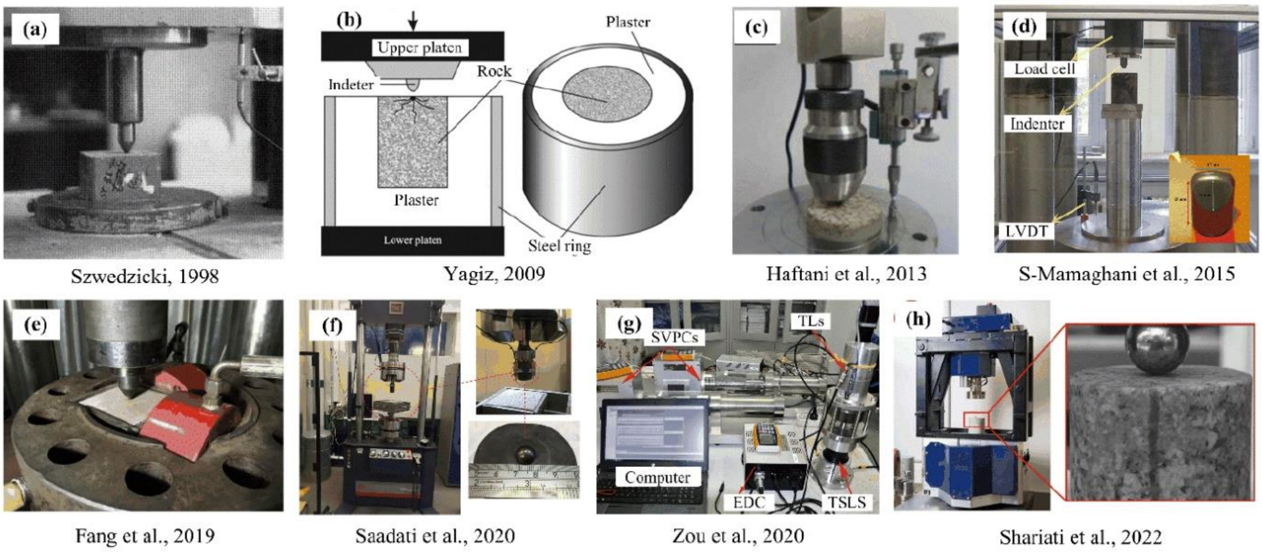


**Fig. 5.** Categorization of Studies Conducted in the Field of Rock Brittleness Index

### A. Laboratory Studies

Many researchers have evaluated the rock brittleness index on a laboratory scale. Figure 6 illustrates some of the laboratory studies on the rock brittleness index using the penetration test. Hucka and Das (1974) mentioned that the concept of brittleness is not fully elucidated yet. In brittle and fragile rocks, the fracturing is of the brittle type, and cracks propagate within the rock matrix during penetration of the tool. High compressive-to-tensile strength ratio, high reversibility, high internal friction angle, and formation of fine particles upon fracturing are among the other important characteristics of rocks. George (1995) defined brittleness as follows: the ability of rock materials to undergo continuous and uninterrupted deformation without significant change in their apparent shape simultaneously with the application of stresses greater than the stress required to form micro cracks in the rock. A general rule in the field of rock brittleness is that more brittle rocks break with much less deformation.



Szwedzicki, 1998 Yagiz, 2009 Haftani et al., 2013 S-Mamaghani et al., 2015

Fang et al., 2019 Saadati et al., 2020 Zou et al., 2020 Shariati et al., 2022

**Fig. 6.** Examples of Penetration Testing Devices (Fang et al. 2019; Haftani et al. 2013; Saadati et al. 2020; Shariati et al. 2022; Shaterpour-Mamaghani et al. 2016; Szwedzicki 1998; Yagiz 2009; Zou et al. 2020)

### B. NUMERICAL STUDIES

While experimental rock mechanics provide valuable insights into the rock failure process, penetration into the rock, and crack propagation, conducting comprehensive experiments to explore various conditions such as sample size, penetration rate, and confined pressure can be costly. Fortunately, advances in computer technology have opened avenues for researchers to investigate rock penetration numerically using computational techniques. Numerical simulations offer cost-effective and reproducible tools for conducting multiphase simulations. Theoretical mechanics categorizes numerical methods into three main classifications: continuum methods, discontinuum methods, and combined continuum-discontinuum methods. These approaches leverage the computational power of computational tools to model and analyze rock penetration, thereby enabling more efficient and systematic exploration of the fundamental factors affecting the process. Some of the past numerical studies on rock brittleness index are listed in Table 1.

### C. INTELLIGENT STUDIES

Despite the widespread use of machine learning techniques for solving engineering problems, a very limited number of studies have utilized these techniques for analyzing issues in the field of rock brittleness index (BI). A summary of some of these studies is provided in Table 2.

**Table 1.** Some of the Past Numerical Studies on Rock

| Topic | Method | Reference |
|---|---|---|
| Numerical analysis using finite difference method with Mohr-Coulomb elastoplastic properties | FLAC | (Cabezas & Vallejos 2018) |
| Mechanism of rock brittleness effect on rock fragmentation and cutting performance | UDEC | (Xuefeng et al. 2018) |
| Detection of brittleness effect on hydraulic fracturing behavior of gilsonite with considering rock heterogeneity | RFPA | (Li et al. 2021) |
| Study of damage-fracture behavior and associated micro-crack process in compact crystalline rocks under complex loading conditions | PFC | (Hu et al. 2023) |
| Estimation of rock brittleness index based on grain characteristics on artificial and digital rock images | FLAC | (Lubis et al. 2022) |
| Experimental cutting tests for detailed examination of angle and bedding brittleness effects on rock cutting behavior | PFC | (Mortezaei et al. 2023) |
| Focus on the effect of grain size on stress-dependent permeability in porous rocks using discrete element method | PFC | (Duan et al. 2023) |
| Development of a uniaxial compression model for fractured rocks | PFC | (Yuan et al. 2023) |

**Table 2.** Summary of Intelligent Methods for Predicting Rock Brittleness Index

| Reference | Methodology |
|---|---|
| Yagiz & Gokceoglu 2010 | Fuzzy logic and regression models |
| Kaunda & Asbury 2016 | Artificial neural networks |
| Yagiz et al. 2018 | Particle swarm optimization and genetic algorithm |
| Mikaeil et al. 2018 | Fuzzy logic |
| Hussain et al. 2019 | Colonial competitive algorithm and particle swarm optimization |
| Wood 2021 | Box optimization algorithm |
| Armaghani et al. 2020 | Support vector machine |
| Sun et al. 2020 | Auto-interaction detector, random forest, support vector machine, k-nearest neighbors, artificial neural network |
| Filanovich & Povzner 2020 | Gradient boosting, random forests, artificial neural networks, support vector machines |
| Yagiz et al. 2020 | Differential evolution algorithm |
| Xiong et al. 2020 | Random forest regression |
| Hou et al. 2022 | Support vector machine, neural network, multivariable regression, classic machine learning algorithm, multiple linear regression, support vector regression, artificial neural network |
| Shahid & Kargaranbafghi 2021 | Multivariable regression |
| Shahid et al. 2022 | Univariable regression and bivariable regression |
| Li et al. 2023 | Field regression analysis |

### D. THEORETICAL METHODS FOR PREDICTING ROCK BRITTLENESS INDEX

Analytical models in rock mechanics studies use principles and mathematical equations to describe the mechanical behavior of rocks and rock structures. These models employ precise analysis and theoretical approaches to address mechanical issues. Below are some of the most important analytical models in rock mechanics: shape analysis models, limited strain-stress models, crack models and their extensions, Hook models, and coupled indentation models (Feng et al., 2018, Anvari et al., 2010). The Hook model is a fundamental model in rock mechanics that operates based on Hooke's law. This model assumes that stress and strain in an elastic medium are directly proportional. Typically, this model is used to describe the elastic behavior of rocks at low stress levels. The limited strain-stress model investigates rock deformation under tensile and compressive stresses. With experienced stress and strain within the elastic range, the limited strain-stress model can assist in determining the mechanical properties of rocks (Fu et al., 2022). The coupled indentation model is analyzed based on finite indentation analysis and studies deformations and stresses in a rock structure under different loading conditions, especially for nonlinear behavior and ductility of rocks. Crack models and their extensions are used to analyze and predict rock behavior in the presence of cracks. These models may examine the effects of cracks on rock strength and ductility and consider the analysis of dynamic phenomena. Shape analysis models are employed to analyze the shapes of rocks. Geometric and mathematical theories may be used to determine the shape and geometric properties of rocks (Zhong et al., 2023, Katibeh et al., 2012). Analytical models offer their advantages in accuracy in analyzing the mechanical behaviors of rocks. However, they require simplifying assumptions and may prefer numerical or empirical models for more complex cases.

## III. SUMMARY

By comparing the literature on predicting rock brittleness index, it can be observed that the methods used tend to complement each other, each having its own advantages and disadvantages, as outlined in Table 4.

Szwedzicki (1998) came to the conclusion that the indentation hardness index (IHI) could be calculated as the ratio of the force (F) to corresponding penetration (P) in kN/mm using the initial elastic-linear phase of the force-penetration profile (Szwedzicki 1998). According to Yagiz (2009a), the test's three distinct force-penetration profile phases may be utilized to represent different rock characteristics and investigate the brittleness behavior of the rock under indenters or disc cutters. As a result, the brittleness index (BI) in kN/mm was calculated using the slope of the force-penetration profile for its entire phase. This was done by drawing a line from the chart's origin to the highest applied force that the rock could absorb before the test was terminated (Fig. 6) (Yagiz 2009).

The following formula uses Fmax, which stands for maximum applied force on a sample in kN, and P, which stands for comparable penetration in mm (Eq. 1):

$$BI=\frac{F_{max}}{P} \quad (1)$$

Due to significant force drops and big chips, high brittle rock on the chart (Fig. 7) exhibits a fluctuating force-penetration profile, whereas moderate brittle rock shows a little force drop and tiny chips. Because the rock is low brittle or ductile, there is only smashing against it rather than forceful falling and chipping.

**Table 3.** Summary of Theoretical Prediction Methods for Rock Brittleness Index

| Reference | Objective | Achievement |
|---|---|---|
| Meng et al. 2015 | Characterizing rock fracture based on stress-strain curves | Proposing an evaluation method |
| Feng et al. 2018 | Static and dynamic Young's modulus and Poisson's ratio based on the theory of elastic wave in rock | Reservoir classification based on fracture |
| Soleiman Dehkordi et al. 2019 | New empirical equations for predicting the modulus of rock mass drop using fracture indices | Using the Hooke and Dirichlet approach to estimate strain change modulus, considering factors such as virgin rock modulus, disturbance factor, and GSI |
| Fu et al. 2022 | A mechanical damage model for simulating the frozen rock fracture process based on statistical damage theory, Hooke-Brown criterion, and strain difference function | A new fracture index for frozen rocks using energy-based method based on three-axis experiments on saturated red sandstones to investigate the mechanical properties and fracture of frozen rocks |
| Cheng et al. 2022 | Prediction method of reservoir fracture based on Mohr-Coulomb failure criterion and in-situ stress principle | Mathematical relationship between rock mechanical properties and in-situ stress, considering parameters such as Poisson's ratio, confining pressure, maximum horizontal stress, and minimum horizontal stress |
| Zhong et al. 2023 | A new index | High rock fracture meaning elastic energy |
| Xu et al. 2022a | Systematic evaluation methods of common fracture | The effect of common fracture index characteristics on different rock samples based on stress-strain curves |
| Gui et al. 2022 | Evaluation of fracture heterogeneity index for shale | A specific heterogeneous shale fracture index consistent with results of uniaxial compression experiments |
| Gao et al. 2022 | Based on the characteristics of crack initiation before peak and stress drop | Effects of limited pressures and different loading states on rock fracture |
| Yang et al. 2022 | Oliver and Pharr method and energy method | Nanoindentation experiments on shale surfaces to obtain mechanical properties |
| Xu et al. 2022b | Damage constitutive model of rock based on equivalent strain hypothesis of Lemaitre and energy dissipation theory | Elastic modulus change for thermal damage definition (DT) and damage evolution curves at different temperatures |
| Gao et al. 2023 | Feasibility study of the method using granite, sandstone, and marble data under different conditions | Proposing a fracture evaluation method based on statistical damage parameters of rocks |
| Zheng et al. 2023 | Based on the characteristics of energy conversion after peak under actual triaxial stress conditions | Proposed evaluation index for intrinsic fracture triggering nature of rocks from an energy perspective |

**Table 4.** Comparison of Various Methods for Evaluating Brittleness Index

| Study Method | Advantages | Disadvantages |
|---|---|---|
| Experimental | Detailed analysis of material structure, examination of mechanical properties, enhancement of research quality and technology development, determination of material safety and strength, innovation research, validation and improvement of theoretical models | The complexity and time-consuming nature of some experiments, limitations in the number of variables, the need for controlled conditions, environmental impacts, human error, constraints in conducting hazardous experiments, challenges in result reproducibility, limitations in modeling, and system complexity. |
| Numerical | Time and cost savings, capability for accurate modeling, handling of complex structures, analysis of various parameter effects, validation capability. | Dependency on input data, limitations in approximation, complexity and requirement for expertise, challenges in validation, need for computational resources, calibration requirement using real and laboratory data (dependent on experimentation). |
| Intelligent | Rapid data processing, ability to generalize, recognition of complex patterns, reduction in the need for precise physical modeling. | Dependency on data, complexity of interpretability, need for large volumes of training data, sensitivity to outliers, requirement for technical expertise. |
| Analytical | Precision in modeling, interpretability, suitable for limited data, applicable at both small and large scales. | Reliance on assumptions, limited by available data, may not capture all complexities, challenges in scaling up. |

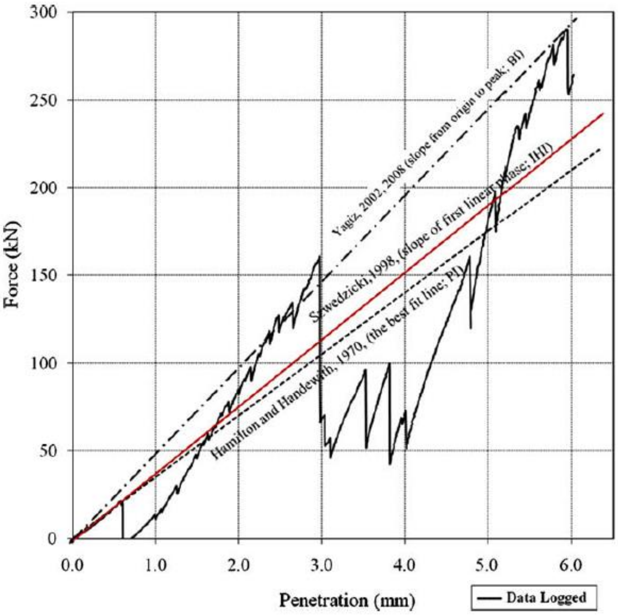


**Fig. 7.** Different representations extracted from the force-penetration diagram of the experiment(Yagiz 2009)

Additionally, using the generated BI and the force-penetration profile produced(Yagiz 2009; Yagiz and Gokceoglu 2010), the rock brittleness could be categorized based on the punch penetration test, as shown in (Table 5).

**Table 5.** Punch penetration test-based categorization of the brittleness of rocks

| Brittleness index (kN/mm) | Brittleness class |
|---|---|
| ≥ 40 | Very high brittle |
| 35–39 | High brittle |
| 30–34 | Medium brittle |
| 25–29 | Low brittle |
| 20–24 | Low brittle |
| ≤19 | No-brittle (ductile) |

## IV. CONCLUSIONS

The importance of rock fracture indices within materials engineering and mining sectors presents a significant challenge, urging for further exploration and advancement. This article delves into a comprehensive review of recent studies in this domain, shedding light on the multifaceted nature of these investigations, encompassing experimental, numerical, intelligent, and analytical methodologies. While experimental inquiries, particularly those delving into the mechanical properties of rocks, lay the groundwork, they call for refined methodologies and elevated standards. Numerical analyses offer the ability to simulate the intricate behavior of rocks across diverse environmental conditions but require improvements in model construction and parameter selection.

Additionally, intelligent and analytical techniques play a crucial role in accurately interpreting data but demand careful examination of limitations and inefficiencies. Therefore, this critical evaluation not only contributes to strengthening the technical and scientific foundations of recent research on rock fracture indices but also serves as a guiding beacon for future endeavors in this scientific realm. By addressing these constructive criticisms and embracing advancements, ongoing research endeavors hold the promise of yielding more precise and reliable insights into the realm of rock fracture, paving the way for further advancements and innovations.

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