

Review

A Comparative Review of Mechanical and Petrographic Properties and Their Role in Estimating the Brittleness Index of Norite: Implications for Geomechanical Applications

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Abstract: Norite is a coarse-grained mafic igneous rock dominated by essential calcic plagioclase and orthopyroxene. Norite is known for its toughness, and it has a high compressive strength which makes it important in engineering. This paper examines the mechanical and petrographic properties of norite, including their relevance to geomechanical applications. Despite improvements in brittleness estimation, standardizing brittleness indices remains a challenge due to geological variability, incompatible petrographic techniques, and difficulties in relating mineral composition to mechanical behavior. Current brittleness models mainly rely on mechanical properties, often ignoring key petrographic factors like grain size, mineral composition, alteration, and porosity. This limits their accuracy, especially for complex rocks like norite. Few studies integrate both petrographic and mechanical data, creating a gap in fully understanding the geomechanical behavior of norite. This review was carried out by examining the origin, formation, and petrographic properties of norite, and a comparative analysis of its strength, flexibility, mineral structure, and fracture mechanics was conducted, highlighting their importance in the engineering and mining industries. The results of this study highlight how factors like strength, brittleness, and durability influence norite's suitability for geomechanical applications in mining, tunneling, and construction. Furthermore, the results outline that the mineral composition of norite affects its strength, with quartz enhancing strength and altered minerals like feldspar, mica, and biotite weakening the rock and making it more prone to fracturing. These results are important for tunneling projects as they help predict how rocks will behave, ensuring tunnel stability and better design in underground support systems.

Keywords: norite; brittleness index; mechanical properties; petrographic properties; rock strength



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1. Introduction

Norite is a plutonic igneous rock primarily composed of plagioclase feldspar and pyroxene minerals. It is formed through the slow cooling of magma deep within the earth's surface, creating a strong and durable rock. The use of norite is extensive within the engineering space due to its compressive strength, resistance to abrasion, and stability. In civil engineering, it is preferred as a road aggregate and is used in foundational work, whereas in mining, it is frequently contained in mineral bearing resources such as chromite and platinum group elements (PGMEs), amongst others, with a higher proportion of orthopyroxene.

In South Africa, norite in the Bushveld Igneous Complex (BIC) is identified as having a shear plane of weakness within confined regions of the rock, which can vary in continuity depending on the applied stress conditions [1]. Shear planes can either be continuous, extending smoothly across the material, or discontinuous, breaking into segments, depending on factors such as the material properties, stress conditions, and the presence of pre-existing weaknesses [2]. A study by Waterton et al. [3] (2020) reported norite as an igneous rock comprising low titanium dioxide concentrations (0.1–0.7 wt% TiO_2), high bulk rock magnesium (0.57–0.83 wt% Mg), and high silica contents (52–60 wt% SiO_2). According to Hunt et al. [4] (2018), a rock is considered norite if it contains both primary pyroxene and plagioclase with the prefix leuco applied when the rock consists of 65% to 90% of plagioclase.

The eastern bushveld complex norite, particularly above Upper Group 2 (UG-2), is crucial in engineering and mining due to its strength. However, the fractures that occur in norite that act as weak planes can impact mining excavation, highlighting the need to understand rock strength based on its mechanical properties and mineralogical content [1]. Khalifeh et al. [5] (2016) also outlined the importance of norite as it has the potential to be used as a solid precursor in the creation of a new cementitious binder since it contains a higher concentration of plagioclase than quartz. Stratigraphically, norite is found in the Critical Zone of the BIC, which is the most economically valuable zone and serves as the boundary between ultramafic rocks (harzburgites and pyroxenites) and mafic rocks (norites and gabbro-norites) [1].

Comparing the mechanical and petrographic properties of norite helps geologists and rock engineers understand its behavior under different conditions. Mechanical properties such as strength and elasticity define how rocks react to stress and environmental conditions [6]. Askaripour et al. [7] (2022) provided a factual justification for petrographic analysis importance based on the mineral composition and texture of rocks, offering insights into their formation and behavior. Therefore, it is critical to comprehend the importance of the mechanical and petrographic properties of a rock in order to effectively determine the appropriate method to estimate its brittleness. Askaripour et al. [7] (2022) also emphasized that both short-term and long-term rock behavior can be assessed by considering the interaction of various parameters, such as rock texture and petrophysical and mechanical properties, which are essential for many geoenvironmental applications.

The brittleness of the rock is a key property in determining how the rock breaks or fractures. Moreover, brittleness is an important mechanical attribute of rock masses and a key parameter for evaluating hydraulic fracturing, rock breakage, and explosions [8]. Li et al. [9] (2023) also circumvents the brittleness index as an empirical mechanism parameter to evaluate rock brittleness, which is crucial for resource exploitation, mechanical efficiency, rock burst prediction, and disaster prevention. Consequently, it is worth exploring the applicability of norite to dynamic loads wherein brittleness indexes measure the propensity of a rock to break or fracture under stress rather than undergo plastic deformation [9].

This paper presents a comparative review of the mechanical and petrographic properties of norite, focusing on rock strength, brittleness, mineral composition, and durability. It also explores the correlation between the petrographic and mechanical characteristics of norite, focusing on factors such as crack propagation, toughness, brittleness and mineral texture, grain size, and microstructure. Furthermore, the paper provides recommendations for future research aiming to enhance the use of norite in construction and geotechnical design with a particular focus on its implications for geomechanical applications.

2. Geological and Petrographic Overview of Norite

This section presents a detailed investigation of the formation, mineral composition, and characteristics of norite. It explores the role of pyroxenes and plagioclase feldspar in the geological events that led to the crystallization of norite. The petrographic description also highlights the textures of norite and its mineral effects, and its significance in understanding igneous processes with mineral deposits is outlined in the following subsections.

2.1. Origin and Formation of Norite

The Bushveld Igneous Complex (BIC) is the largest layered igneous intrusion situated in the northern region of South Africa, containing the world's largest known reserves of Platinum Group Metals (PGMs) [10]. The BIC extends for approximately 350 km in an east–west direction, and it is situated in the north-eastern region of the Kaapvaal Craton in Southern Africa [11]. Scoon and Viljoen [12] (2019) added that the BIC intrusion comprises three sill-like mafic to ultramafic lobes or structures, known as the eastern, northern, and western limbs (Figure 1). This review paper focusses on the norite rocks in the eastern region of the eastern limb. Norite is formed through magma intrusion into the earth's crust, crystallizing within layered mafic intrusions at 908 °C with 5.5–6.0 kbar pressure. The geological setting, temperature, and pressure during its formation play crucial roles in determining its mineral composition. These factors influence chemical reactions, mineral stability, and recrystallization processes, ultimately shaping the final mineral assemblage and rock type [13].

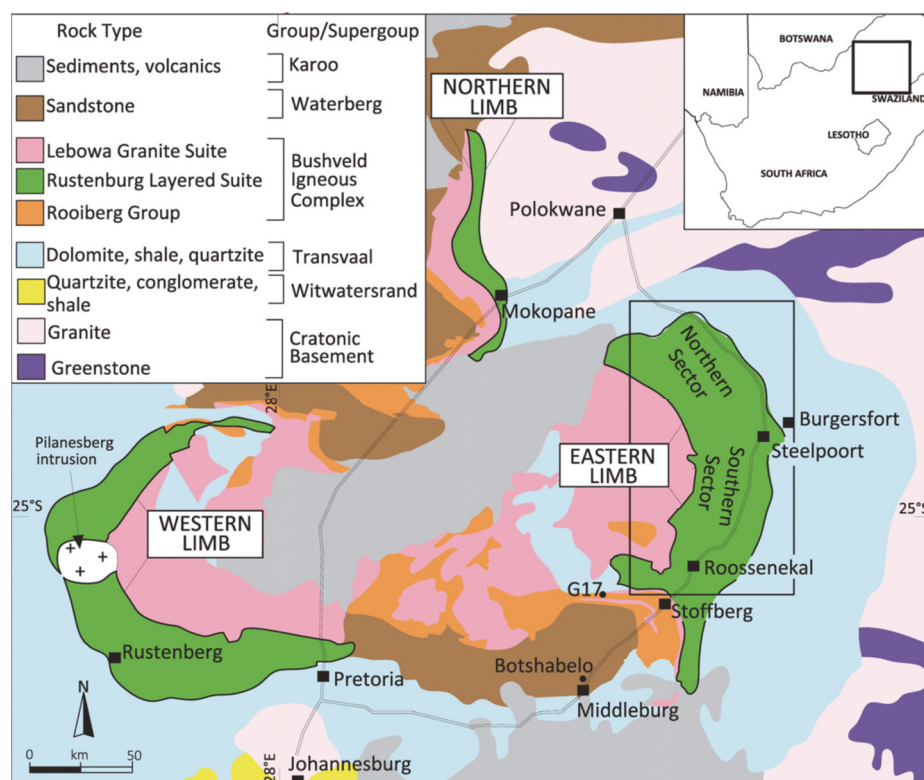


Figure 1. A geological map showing the three limbs of the Bushveld Igneous Complex. The boxed area represents the eastern limb [12].

The formation of the BIC evolved through a combination of structural controls, multiple magma sources, and the emplacement of aphyric magmas and crystal-rich magma slurries, potentially originating from deep staging chambers [14]. Norite formation took place over 2.7 billion years ago (2.7 Ga), during a time of higher geothermal gradients. This involves the concurrent formation of Tonalite–Trondhjemite–Granodiorite (TTG), with

intrusions occurring alongside granulite facies metamorphism and crustal contamination of mantle-derived magma [3]. In addition, Wilson [14] (2015) explained that norite is formed through the crystallization of a mafic magma rich in iron and magnesium, which undergoes differentiation over time.

The first reference to igneous rocks and minerals in the area now known as the BIC was made by German explorer Carl Mauch in the late 1860s when he first identified norite, chromite, and magnetite on a map of the region [15]. The mafic rocks of the BIC, including norite, were deposited in Southern Africa around 2.06 billion years ago and have remained largely unchanged due to isostatic effects on the thickness of the crust [16]. The geological origin of norite primarily includes plagioclase feldspar and pyroxene, which are found in the Lower Zone and Critical Zone of the eastern BIC [17].

Norite is found in various regions around the world, and its distribution is often associated with specific geological settings. Norite is a common rock that can form through normal igneous processes. However, the norite studied here exhibits a number of characteristics, such as its association with PGMs and the high crystallization of pyroxene and plagioclase, which form part of the complex's distinct layering [18]. These norites are found in the Critical Zone, where feldspathic orthopyroxenite is the dominant lithology, characterized by the presence of plagioclase and scattered Cr-spinel magmatism [12].

According to Waterton et al. [3] (2020), the hanging wall of UG2 and UG3 in the critical zone is primarily composed of norite, which changes to anorthosite in the Bastard Cyclic Unit (which resembles the Merensky Reef but lacks mineralization). The hanging wall of the UG2 and UG3 is made of norite, which has a thickness of roughly 50 m (Figure 2).

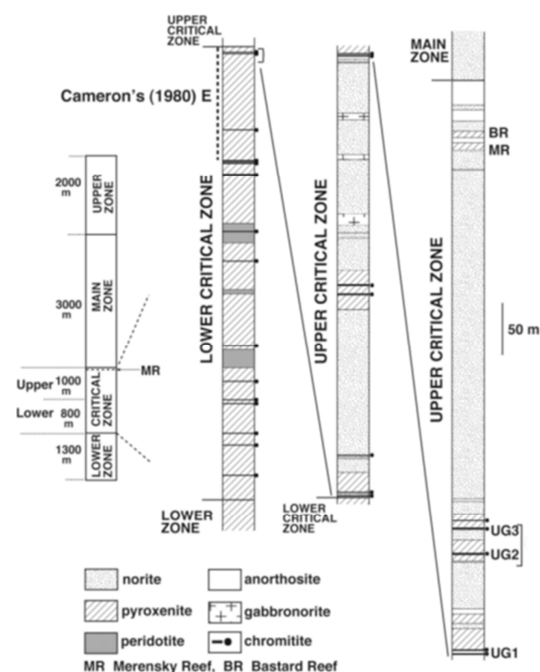


Figure 2. Stratigraphic groups and their thicknesses [19].

Since the key review carried out by Eales and Cawthorn [20] in 1996, the understanding of the BIC has evolved from a system governed by basic igneous petrology principles to a state where virtually none of these principles have escaped serious re-evaluation [21]. Despite over a century of mining and research, the BIC in South Africa remains a focus of modernization and re-examination for the purpose of mining activities and safety measures.

Norite consists of orthopyroxene and plagioclase mineralization, which are formed through fractional crystallization in mafic magma. This unique mineralogy is attributed to the crystallization of olivine and pyroxene, which adhere to the stream of the Bowen

reaction series [22]. Bowen [23] (1928) proposed that norite could form through pelitic assimilation through Bowen's reaction wherein clinopyroxene (Cpx) and aluminosilicate combine to produce anorthite (An) and orthopyroxene (Opx). Beard et al. [18] (2017) additionally stated that norite forms through the fractional crystallization of mafic magma, following Bowen's reaction series, where the crystallization of olivine, pyroxene, orthopyroxene, and plagioclase together creates its distinctive mineralogy.

Arndt et al. [24] (2005) proposed that the magma supplied to the BIC was from a deeper chamber that gradually assimilated surrounding crustal rocks. The emplacement of the Norite Belt was soon followed by high-temperature, low-pressure granulite facies metamorphism at around 800 °C and less than 9 kilobars (kbar). These conditions suggest high temperature gradients (>900 °C/GPa) and that the norite magmas were intruded into relatively thin crust and lithosphere [3]. Waterson et al. [3] (2020) proceeded to clarify that the simultaneous formation of TTGs and norite, followed by high-temperature, low-pressure metamorphism and crustal contamination, is a process that is limited to norites older than 2.7 Ga. The swift reduction in pressure from gabbro to norite (from 8 kbar to 3 kbar), with only a minor drop in temperature, may be due to a short duration of magma transfer from the chamber to the pluton emplacement or rapid exhumation [25].

2.2. Petrographic Properties of Norite

The attributes of the major accumulated minerals in norite are characterized by their texture, mineral composition, and variations in mineral proportions [26]. Grain size, packing density, mineral contact types, and mineral composition (primarily plagioclase and orthopyroxene) are the main petrographic factors affecting the characteristics of norite [27]. These variations (grain size, packing density, mineral contact types, and mineral composition) influence the brittleness and strength of the rock as well as the reaction of the rock to stress. In general, a coarse grain size, high feldspar content, and well-developed mineral contacts enhance the mechanical stability of the rock [27,28]. These properties are key factors in determining the ability of a rock to withstand stress-induced damage.

The minerals in norite possess varying mechanical properties, such as strength and stiffness, which contribute to the overall heterogeneity of the rock [27]. The strength and weathering resistance of norite are influenced by its feldspar content, as Khorasani et al. [28] (2019) detailed that plagioclase feldspar, pyroxene, and anorthite are minerals that make up 60–80% of norite rock. Nouri et al. [27] (2022) also added that 20–30% of norite is made of orthopyroxene, which is usually enstatite or hypersthene, influencing the mechanical strength and brittleness of the rock.

Norite visually displays a coarse-grained texture with large, visible mineral crystals, which result from slow crystallization that occurred deep within the earth's crust. Norite contains an insignificant amount of olivine and has accessory minerals such as magnetite and ilmenite, which contribute to its density and texture [28]. The strength of the rock is influenced by its grain size, wherein coarser grains often have higher mechanical strength [7].

Norite exhibits a porphyritic texture, with larger crystals of plagioclase or orthopyroxene set within a finer-grained matrix (Figure 3). This arrangement can affect how the rock reacts to external stress, resulting in higher mechanical strength [27]. Khorasani et al. [28] (2019) examined the packing density of the rock and discovered that the solidity of norite is enhanced by the stacked packing of plagioclase and orthopyroxene grains, which improves its strength. Furthermore, Nouri et al. [27] (2022) conducted a study on the grain area ratio and emphasized that the grain area ratio (GAR) measures the proportion of individual

mineral grain areas to the total rock area (see Equation (1)), with a higher GAR indicating better mineral interlocking and greater rock durability.

$$\text{Grain Area Ratio (GAR)} = \frac{\text{mineral grain}}{\text{total rock area}} \quad (1)$$



Figure 3. A norite specimen displaying its coarse texture.

The GAR (grain area ratio) represents the proportion of the total area occupied by grains relative to the overall area analyzed in a selected thin-section image. It quantifies the grain content as a percentage of the reference area observed under the microscope. The GAR specifically refers to an area ratio, not a volume ratio [27].

A thin-section examination is used to analyze the petrographic aspects of norite by observing its mineral composition, texture, and optical qualities under a polarizing microscope. The geometric characteristics of mineral grains can be determined through visual examination, microscope examination, and automated analytical element mapping techniques [29]. Toshio [30] (1974) depicted that norite composed mainly of plagioclase, hypersthene, olivine, hornblende, augite, and cummingtonite has a medium-grained texture with a hypidiomorphic–poikilitic structure through thin-section analysis.

2.3. Influence of Petrographic Properties on Mechanical Behavior

The mineralogical attributes of rocks have a significant impact on their mechanical qualities. Malki et al. [31] (2024) state that the mechanical properties of a rock, which are influenced by its mineral composition, determine whether it is weak, strong, ductile, stiff, or brittle. Eberhardt et al. [32] (1999) examined grain size as an important petrographic characteristic, suggesting that the initial cracking stage occurs due to stress load irrespective of the average grain size. This occurs in rocks with a uniform mineral composition and consistent grain size distribution. Malki et al. [31] (2024) further discuss that the presence of quartz strengthens rocks, while altered feldspar, mica, and biotite weaken rocks. Weaker or altered minerals, like mica and feldspar, can weaken a rock, making it more vulnerable to fracturing, whereas minerals such as quartz help to increase the strength of rock [14].

The medium grain size texture in norite balances strength and workability, preventing excessive brittleness or ductility, while coarser textures may lead to lower strength and cracking resistance [31]. Generally, smaller grains are stronger and more resistant to crack propagation because they have more grain boundaries that prevent cracks from spreading.

However, very fine grains may lead to higher porosity, potentially weakening the rock. In contrast, larger grains or coarse-grained rocks may have fewer grain boundaries, making them more inclined to fracture under stress [33].

According to Malki et al. [31] (2024), the uniaxial compressive strength (UCS) of felsic norite varies between 142.6 MPa and 217 MPa, with an average of 188.6 MPa. Additionally, the study showed that the tangent Young's modulus of elasticity ranges from 62.17 to 71.4 GPa, averaging to 67.4 GPa. Additionally, the Poisson's ratio ranges from 0.19 to 0.28, with an average of 0.19 based on the norite samples used by Malki et al. [31] (2024). In order to determine the influence of the petrographic characteristics on the mechanical properties, the ratio of quartz to plagioclase and the grain size were correlated with the engineering properties using regression analyses [34]. A strong correlation was observed between the UCS, point load strength, and tensile strength in the study of Keikha and Keykha [34] (2013), focusing on the strength of granitic rocks, which is significantly influenced by mineral composition. According to Malki et al. [31] (2024), the UCS can only be estimated by using the average value obtained from testing other samples of the same rock type.

Grain boundaries can act as weak points where cracks start and propagate, while alterations in mineral composition can reduce cohesion, increase porosity, and promote crack growth. The study by Göğüş et al. [35] (2024) highlights the significant role of rock texture in microcrack formation, emphasizing its importance in rock engineering applications. Grain texture characteristics (shape, size, orientation, and heterogeneity) are a key parameter governing the response to stress. Grain texture controls the strength and ductility of crystalline rock; however, it can be challenging to incorporate these factors in a quantitative manner [36]. Peng et al. [37] (2017) additionally emphasized the fact that brittleness indices are based on the concept that rock breaks with increases in tensile strength, implying that as the compressive-to-tensile-strength ratio decreases, the rock is more prone to brittle behavior and breaking.

Norite is a coarse-grained mafic intrusive rock primarily composed of orthopyroxene and plagioclase feldspar, often accompanied by clinopyroxene and olivine (Figure 4). The petrographic image displays a coarse grain size, and it tends to have reduced strength due to easier fracture propagation. The study of Bieniawski [38] (1974) supports this by showing that adding finer textures improves rock durability and resistance. Strong interlocking textures between mineral grains enhance compressive strength, whereas alteration zones and weak grain boundaries compromise structural integrity [39].

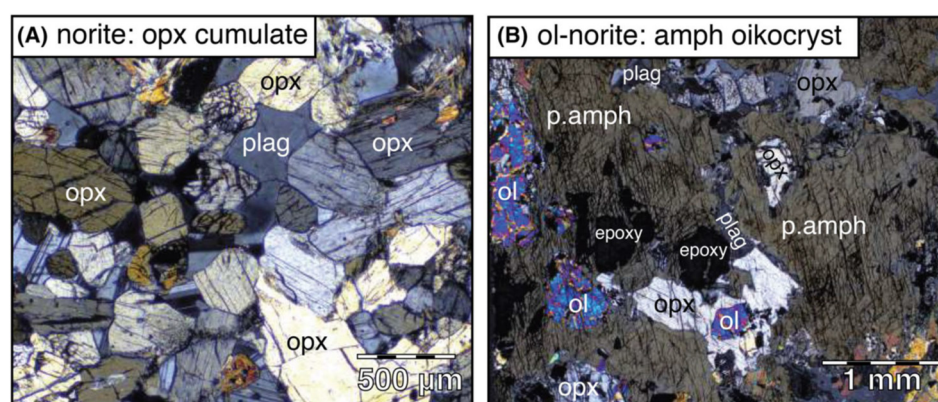


Figure 4. A petrographic image of norite specimen displaying its coarse texture [40].

A thin-section analysis was performed using standard petrographic microscope settings, including magnifications between 25× and 100× under both plane-polarized light (PPL) and cross-polarized light (XPL). A 360° rotating stage allowed for mineral orientation analysis, while polarization helped distinguish mineral types, alteration zones, and textural

features such as grain boundaries and microcracks. These parameters are essential for evaluating the influence of petrographic characteristics on the mechanical behavior of the rock [41].

3. Mechanical Properties of Norite

The mechanical properties of rocks include the compressive strength, tensile strength, hardness, elasticity, and fracture toughness. These are essential for evaluating the behavior of the rock under different stresses and determining its suitability for engineering and geological applications. Despite rising interest in the mechanical responses of rocks to the mechanical properties of norite, a comprehensive understanding of these properties is lacking [42]. This section explores the key mechanical properties of norite, focusing on its strength, deformation, and fracture behavior.

3.1. Strength Parameters

Rock strength properties are significantly affected by weathering, which is often linked to surface exposure or near faults and shear zones, leading to increased clay content and porosity [28]. Additionally, joints and fractures caused by regional stresses and digging up create planes of weakness, allowing fluid passage and contributing to further alteration [42]. Askaripour et al. [7] (2022) define shear strength as the ability of a rock to resist shear forces or the point at which it fails due to shear stress. Therefore, when the rock is subjected to shear load, it slides along a plane, causing failure parallel to that direction.

Uniaxial compressive strength (UCS) is the maximum axial stress a material can withstand under uniaxial compression before failure occurs. UCS is an essential mechanical property, measured by applying a compressive load to a specimen in a controlled laboratory setting until failure occurs, at which point the maximum stress is calculated [43]. Uniaxial compressive strength (UCS) is commonly measured in laboratories, but alternative methods such as the point load index and field press are also used in practice [44]. UCS testing involves compressing rock cylinders parallel to their long axis, with the accuracy of the test relying on flat, perpendicular platen surfaces [45]. The strength of the sample decreases with an increasing length-to-diameter ratio, and failure typically occurs at a strength lower than the sample's maximum UCS; failure also occurs due to rapid energy release. Errors can arise from frictional effects at the platen contact, and in strong materials, both longitudinal splitting and shear fractures may occur [46].

The study by Wilson et al. [1] (2005) outlined that the UCS of norites in the Merensky Reef ranges from under 100 MPa to over 200 MPa, with an average of 150 MPa for the freshest rocks. The tensile strength (TS) of norites ranges from less than 5 MPa to 15 MPa, with a mean of 11 MPa, classifying most norite rocks as strong to very strong [1,31].

In Figure 5, Wilson et al. [1] (2005) conducted UCS testing on igneous rock samples where a 60 mm diameter core typically failed along a plane angled at less than 45° to the vertical compression axis. The failure modes observed included (a) failure along a single plane, (b) failure along a single plane with high-angle longitudinal fractures, and (c) failure along two fractures symmetrically inclined to the longitudinal axis. Rock failure modes are influenced by factors such as mineral composition, stress distribution, material strength, and testing conditions, which are essential for predicting rock behavior in mining. The unique composition of norite results in distinct failure modes [1]. Shear planes can be either continuous, extending smoothly across the material, or discontinuous, breaking at certain points [31]. The findings of this study are significant as they focus on norite, specifically from the Bushveld Complex, which is the same subject of this research. Moreover, both studies observe similar behavior in norite under uniaxial compressive strength (UCS) testing.

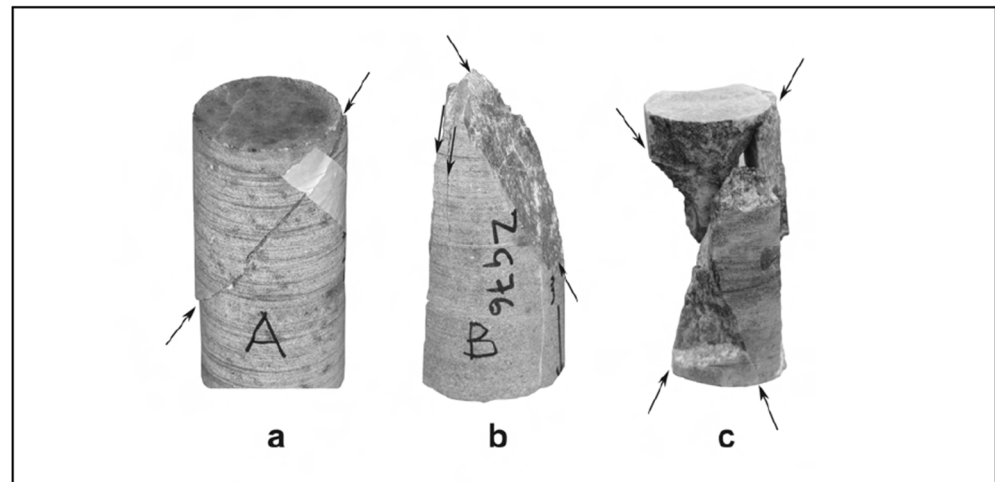


Figure 5. The core rock samples that were subjected to UCS testing. (a) Failure along a single plane failure; (b) failure along a single plane failure with high angle longitudinal fractures; (c) failure along two fractures symmetrically inclined to the longitudinal axis [1]. (Source: authors' own experimental work (Wilson et al., [1] 2005).)

A 60 mm diameter core was used for UCS testing, with samples typically failing along a plane inclined at less than 45° to the vertical compression axis (Figure 5). According to the ISRM guidelines, the recommended loading rate for standard UCS testing is between 0.5 and 1.0 MPa/s. The tensile strength is the maximum stress a material can withstand when pulled before breaking. The direct tensile strength is measured by applying a uniaxial tensile load to a specimen until it fractures; in contrast, the Brazilian tensile strength is determined by applying a compressive load to a disk-shaped specimen, causing it to fail in tension [47]. The study of Perras and Diederichs [48] (2014) reviewed rock tensile strength to investigate the relationship between direct tensile strength (DTS) and Brazilian tensile strength (BTS). It also evaluated the reliability of estimating tensile strength using properties such as the crack initiation (CI) threshold. The findings of this study on tensile strength indicate that accurately estimating the true tensile strength from other laboratory results is challenging, with estimates based on UCS values yielding the most unreliable results. Therefore, direct tensile testing is considered the most reliable method for determining the true tensile strength of a rock as it involves minimal external influences when conducted correctly [49]. Thus, the DTS should be regarded as a key strength parameter for norite in this study. The direct tensile strength test yielded lower strength values than the Brazilian tensile strength test as the direct tensile strength test is affected to a greater degree by the presence of microfractures and micro fissures in the rock.

To obtain accurate tensile strength measurements, it is crucial to consider alternative specimen designs and testing methods proposed by other researchers. Brace [50] (1961) recommended the dog bone shape for direct tensile specimens, with a height-to-diameter ratio of 2.0–3.0 in the central test region and a fillet curvature radius of 1–2 times the diameter. This shape helps reduce stress concentrations at the specimen ends, allowing for authorized testing using grips that pull against the ends of the specimen or vertical edges (Figure 6a). Square dog-bone-shaped specimens can still result in stress concentrations, leading to invalid failure outside the central area (Figure 6b,c). Gripping cylindrical specimens can also cause stress concentrations at the ends, invalidating the test if failure occurs near the grips (Figure 6d). Fairhurst and Cooke [46] (1966) suggested cementing end caps to reduce stress concentrations, but this can cause torsional failure; alternatively ball joints are recommended for proper alignment.

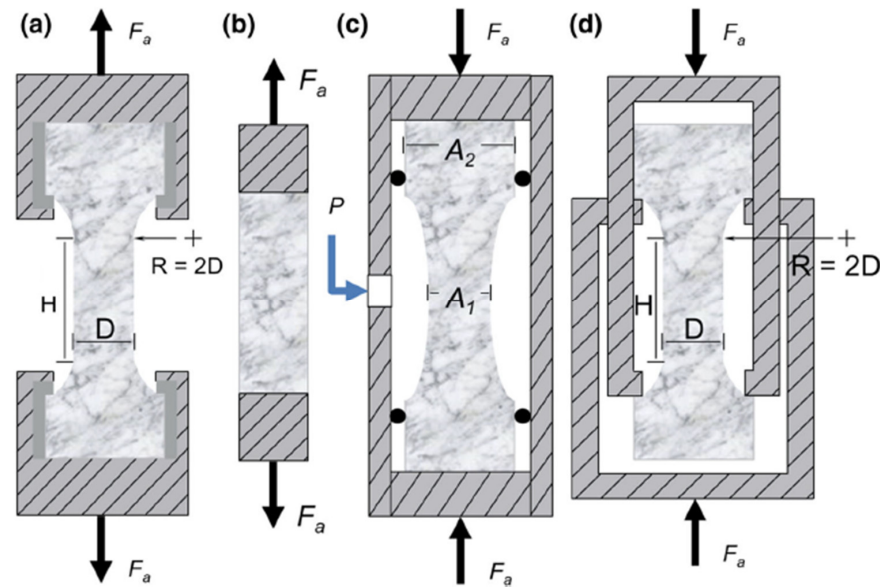


Figure 6. Split grips for dog-bone-shaped specimens are one type of direct stress testing method. (a) For cylindrical specimens, bonded end caps are used. (b) Uniform cylindrical specimen compressed under applied force (F_a), with no necking. (c) Testing for biaxial extension and (d) load converters that convert compression to tension. (Applied force (F_a), radius (R), diameter (D), area (A), and water pressure (P) are crucial variables in these experiments [50].)

UCS tests were conducted on cylindrical rock specimens with a diameter (D) of 54 mm and a height (H) of approximately 108 mm, maintaining the standard 2:1 height-to-diameter ratio, as shown in configurations (a) and (d) in Figure 6. The axial force (F_a) was applied vertically using a loading frame at a constant loading rate of 0.5 MPa/s following the ISRM recommendations ([46,51]).

3.2. Deformation Characteristics

Young's modulus and Poisson's ratio are important for addressing geomechanical issues. However, the determination of the deformation modulus and Poisson's ratio of rock masses depends on the rock mass quality and various geological features [52]. The Poisson's ratio is an elastic constant that measures the lateral deformation of a material when subjected to uniaxial tension or compression [53]. The Poisson's ratios of various rocks vary significantly; for example, norite ranges from 0.2 to 0.25 are observed in Figure 7. For example, marble, which is relatively uniform in composition, has a Poisson's ratio range from 0.15 to 0.30. This wide variability in Poisson's ratios is largely due to the heterogeneities in rocks, influenced by their geological history, mineral content, crystallization, and depositional structure [2]. A small Poisson's ratio indicates minimal lateral deformation under axial strain, while a wide range suggests varying degrees of elasticity in materials.

The elastic modulus is made up of two important mechanical parameters for linear elastic materials, which are the Young's modulus (E) and Poisson's ratio (ν), and they are expressed as

$$E = \frac{\sigma}{\epsilon} \quad (2)$$

$$\nu = \frac{\epsilon_{lateral}}{\epsilon_{axial}} \quad (3)$$

where E is the Young's modulus, σ is stress, and ϵ is strain. ν is the Poisson's ratio, $\epsilon_{lateral}$ is lateral strain, and ϵ_{axial} is axial strain. The Young's modulus quantifies a material's stiffness by comparing stress and strain in its elastic region, while the Poisson's ratio

indicates the material's lateral deformation in response to axial stress. Dong et al. [2] (2021) discovered that the Young's modulus describes the strain (ϵ) response to uniaxial stress in the force-applied direction, while the Poisson's ratio describes the response in perpendicular directions.

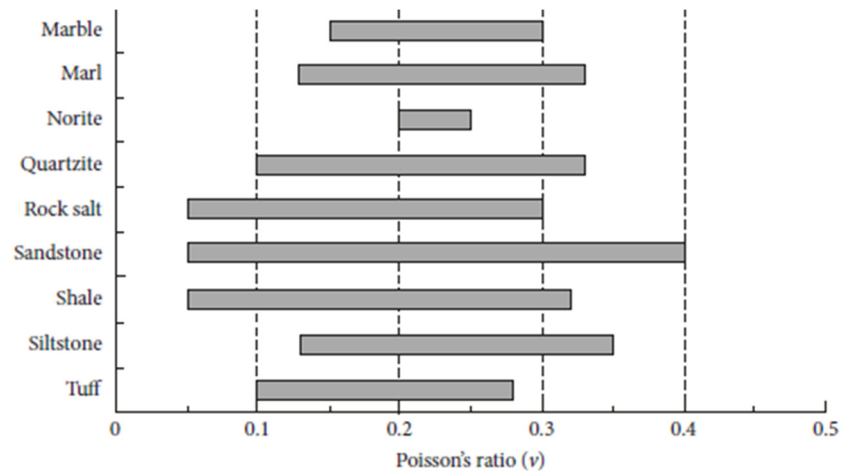


Figure 7. Distribution of Poisson's ratios for different types of rocks (after [54]).

According to the International Society for Rock Mechanics (ISRM), in the study by Davarpanah et al. [52] (2020), the stress–strain curve for axial deformation is the most effective method for determining rock elasticity and the Young's modulus (E). Tangent Young's modulus (E_t) is the slope of the curve at a specific percentage of ultimate strength, while the secant Young's modulus (E_s) is the slope of the line from the origin to a fixed percentage of ultimate strength, typically at 50% (Figure 8). The secant and tangent Young's modulus values in Figure 7 are nearly identical, showing a strong correlation with an R^2 value of 0.99 across all intact rock types, including Monzodiorite, sharing similarities with norite as both are coarse-grained, mafic, and intrusive igneous rocks.

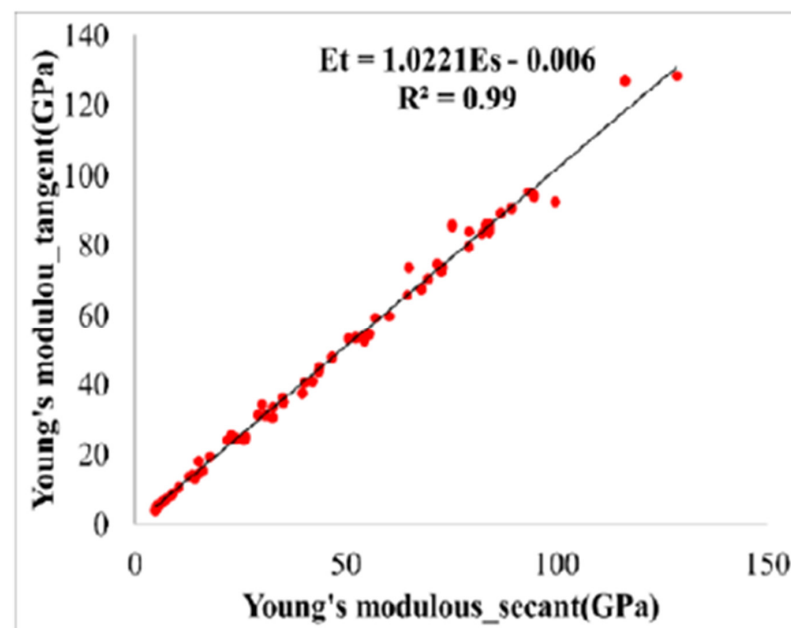


Figure 8. Relationship between secant Young's modulus (E_t) and tangent Young's modulus (E_s) [52]. (Data compiled from Davarpanah et al. [52], 2020.)

The elastic modulus of intact rock (such as norite) is crucial for rock engineering projects like tunnels, slopes, and foundations. This parameter has become a popular area of research due to the need for high-quality core samples, advanced testing equipment, and empirical models to estimate the roughness of a rock [55]. The Young's modulus measures the stiffness of a rock wherein higher values indicate less deformation under load, while lower values suggest greater flexibility and compression.

3.3. Fracture Mechanics

Rock failures occur due to factors such as instability in loading, material faults, deficiencies in structure design, and other unexpected concerns in construction. Enhancing rock-breaking techniques, like blasting or drilling, and designing mining excavations and civil engineering structures all require an understanding of the fracture mechanism of rock [38]. This section discusses cracks and fractures, where cracks are small, surface-level discontinuities caused by initial stress, while fractures are larger, more extensive breaks that can penetrate the entire rock mass. Both are considered weaknesses in geological and mining contexts, significantly influencing the rock's mechanical properties and stability in engineering applications.

In Figure 9, fracture toughness (K_{IC}) is denoted as a key material property that controls the initiation and growth of cracks [56]. A smaller K_{IC} value leads to earlier onset of non-linear behavior, as demonstrated in Figure 9, where volumetric dilation begins at lower stress for smaller K_{IC} values. The apparent Poisson's ratio is influenced by the rock matrix's mechanical behavior and the closure of pre-existing cracks before crack propagation [32]. However, fracture toughness has little effect at low stress levels, whereas at higher stress levels, it causes the Poisson's ratio to increase more quickly for smaller fracture toughness; refer to Figure 9 as an example used to illustrate the fracture toughness of a norite rock.

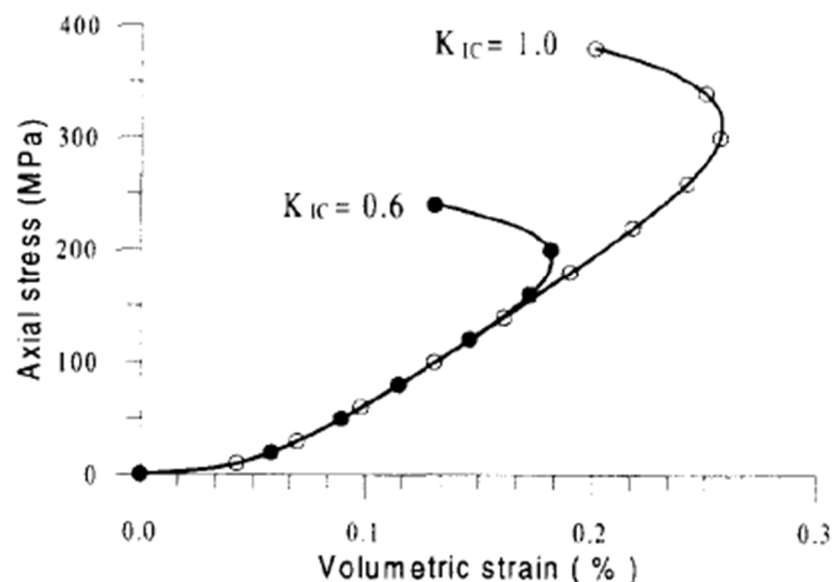


Figure 9. A graph diagram showing the stress–strain curves and stress–apparent Poisson's ratio curves as the fracture toughness varies [57]. (Data compiled from Li et al. [57], 1998.)

Roylance [58] (2001) provided an overview of the energy absorption in rocks, explaining that material toughness is determined by the energy absorbed during crack propagation. Fracture toughness is an essential material property because it directly controls the initiation and propagation of cracks. The increasing strength of rock can increase its brittleness, leading to crack propagation and engineering failures, emphasizing the need for methods to prevent brittle fracture [58]. The Poisson's ratio, influenced by rock matrix mechanical

behavior and crack closure, increases primarily at high stress for smaller K_{tc} values despite remaining unaffected by K_{tc} at low stress [32,57].

For example, Figure 10 in the study of Li et al. [9] (2022) on crack propagation illustrates the relationship between crack propagation in rock and the direction of stress propagation. In rock development, sigma 2 (σ_2) represents the intermediate principal stress, while σ_3 represents the minimum principal stress, and both sigmas play key roles in influencing fracture propagation and orientation. When the initial orientation of internal cracks aligns with the intermediate principal stress, these cracks gradually expand and evolve in the same direction until the rock undergoes macroscopic failure (Figure 10a,b). The stress applied in Figure 10a is less intense compared to that in Figure 10b, where higher stress levels lead to the formation of new initial cracks originating from pre-existing fractures within the rock.

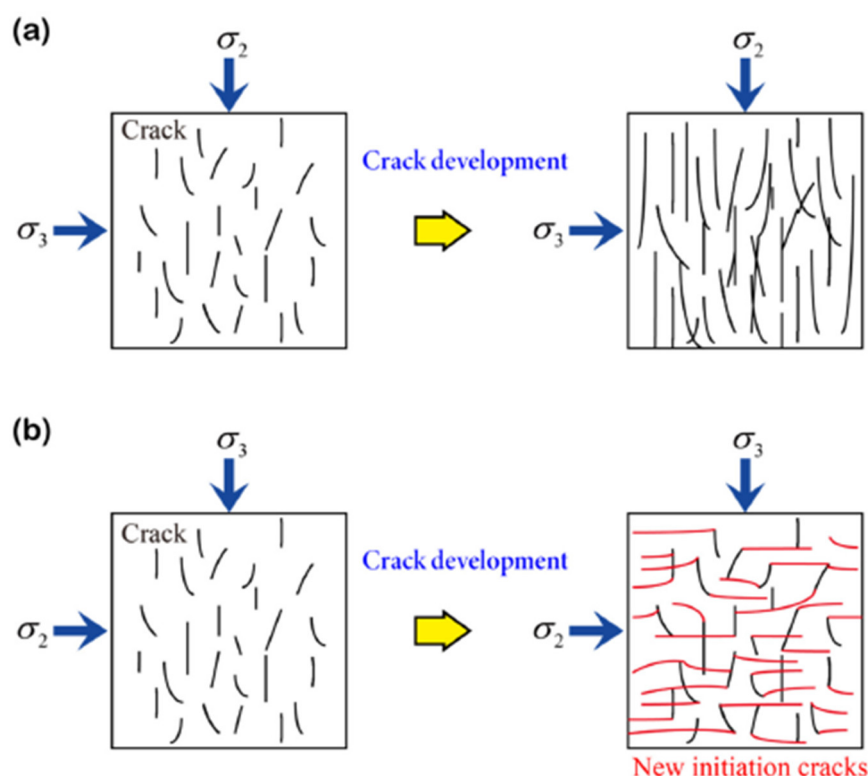


Figure 10. The effect of intermediate principal stress on the propagation law of internal fractures in rock: (a) the initial direction of internal cracks is parallel to σ_2 ; (b) the initial direction of internal cracks is perpendicular to σ_2 [55].

The initiation and growth of stress-induced cracking is a critical step in the brittle failure of rocks, which can lead to dangers such as borehole breakout and the sudden failure of underground excavations in mining and tunneling [59]. Therefore, it is essential to have an appropriate criterion to predict the onset of such damage. Furthermore, Gao et al. [60] (2021) found that ground fracturing effectively controls high-level thick hard strata (THS) by creating horizontal fracture planes. This process splits the THS into smaller layers, reducing its breaking span and lowering mine pressure. Simulations showed that fracturing disrupts the structural integrity of the THS, preventing the formation of large, strong rock structures and thus decreasing its overall breaking strength.

4. Definition and Estimation of Brittleness Indexes

One of the most important mechanical properties of rocks is their brittleness. In rock mechanics, a key property for assessing how a rock fractures are through its brittleness,

which is influenced by factors such as mineral composition, fluid content, and the complexity of the microstructure [61]. The brittleness of a rock depends on mechanical properties such as the unconfined compressive strength (UCS), Young’s modulus, and Poisson’s ratio [62].

Kahraman and Altindag [63] (2004) stated that there are many researchers who have explored various methods for determining brittleness indexes. Unfortunately, there is no universally accepted standardized method or concept for measuring or characterizing the brittleness of rocks [64,65]. Despite the fact that brittleness is significant in many different engineering fields, many researchers noted that there is currently no standardized technique for measuring or quantifying the brittleness indices of different rocks [6,8,33,61,62,66–68]. The method used to quantify the brittleness index could vary based on the type of rock, its material characteristics, and the specific objectives or requirements of the project [62]. Researchers have proposed various methods to quantify the brittleness index, considering factors like stress and strain, mineral composition, and the strength of different rocks, with the reliability of each index varying depending on the specific task at hand.

A compilation of 80 brittleness indices that are publicly available in the rock mechanics literature reveals that these indices are not generally relevant across fields, and they are treated differently based on rock fracture behavior. Additionally, the term “brittleness” is often misrepresented, with many empirically derived indices lacking a theoretical basis and not accurately reflecting rock brittleness [66]. Table 1 categorizes mechanical and petrographic brittleness indices into two groups based on their assessment approaches in this study. The first group uses rock strength parameters from standard tests for brittleness, while the second group uses rock mineral constituent analysis for brittleness.

Table 1. A summary of brittleness indices and the parameters used for their measurements (obtained from Meng et al. [66] (2021).)

Brittleness Indices	Measurement Parameter
B1 to B13	Strength parameters
B14 to B40	Stress–strain curve
B41 to B47	Elastic parameters
B48 to B55	Mineral composition
B56 to B62	Conversional well logging
B63 to B65	Angle of internal friction
B66 to B73	Indentation test
B74 to B75	Fine content
B76 to B77	Consolidation characteristics
B78	Point load test
B79	Pulling test
B80	Micro-scratch test

Meng et al. [66] (2021) outlined that, since 1967, numerous brittleness indices have been developed for various purposes in rock mechanics, classified into two groups, which are stress–strain and mineralogical parameters. These groups are further subdivided into 12 categories based on different parameters or measurement methods. These categories are summarized in Table 1, each offering a unique perspective on the fracture or failure tendency of a material under stress.

Table 1 presents the brittleness indices used for specific parameters, with the main focus of this review paper being the comparison of the mechanical and petrographic characteristics of norite.

Mechanical parameters are measured through physical testing methods, such as hardness, strength, point-load, and penetration tests and tests regarding the inner frictional angle [6,69]. Out of all 12 brittleness indexes reviewed by Meng et al. [66] (2021), only a few (B_1 , B_2 , B_{12} , B_{15-20} , B_{23} , B_{24} , B_{27} , B_{28} , and B_{30-34}) were based on hardness, strength, point-load testing, mineralogical composition, penetration tests, and inner frictional angle and can be used to determine the mechanical behavior of rock.

Petrographic factors such as the grain area ratio, cement content, packing density, packing proximity, and feldspar percentage significantly influence brittleness in rocks [28]. Wu et al. [70] (2023) also emphasized that petrographic properties, such as mineral composition, texture, grain size, and the presence of fractures, are crucial for evaluating the mechanical behavior of a rock and brittleness, which help to predict its tendency to fracture under stress.

The brittleness index of norite is an important parameter that influences the intended or unintended rock failure process in mining, tunneling, and drilling operations. In hard rock tunnels, the brittle failure of surrounding rocks in the form of spalling and rock burst frequently occurs under high geo-stresses [71]. Kivi et al. [68] (2018) stated that various definitions and evaluation criteria for brittleness have been proposed to describe rock failure behavior, but their effectiveness and reliability remain unverified.

Various brittleness indices (B_1 – B_{13}) differ in how they incorporate mechanical parameters such as UCS, tensile strength, elastic modulus, and stress–strain behavior. Indices like B_1 – B_5 are simple and widely used but rely solely on mechanical data, often ignoring petrographic influences [27]. Others, like B_6 – B_9 , integrate stress–strain characteristics and offer better insights into post-peak behavior, making them suitable for rocks showing brittle–ductile transitions [27]. For norite, indices that incorporate both strength ratios and deformation modulus, such as B_7 , B_9 , and B_{11} , are more applicable due to norite’s heterogeneous texture and mineral composition, which influence both stiffness and failure mode. Thus, more comprehensive models better capture norite’s complex mechanical response, especially where altered minerals or grain size variability affect brittleness.

As shown in Table 1, brittleness indices B_1 to B_{13} are based on strength parameters, with index B_1 being the simplest, expressed as

$$B_1 = \sigma_c / \sigma_t \quad (4)$$

$$B_2 = (\sigma_c - \sigma_t) / (\sigma_c + \sigma_t) \quad (5)$$

where σ_c and σ_t indicate the uniaxial compressive strength (UCS) and Brazilian tensile strength, respectively.

Several researchers, such as Singh [72] (1986), Goktan [73] (1991), Gong and Zhao [74] (2007), and Mohammadi [75] (2015), have investigated these two brittleness indices (B_1 and B_2) and concluded that they are commonly used to assess rock fragmentation efficiency. It is also believed that higher values of B_1 and B_2 indicate greater brittleness in the rock (Hucka and Das [76], 1974; Goktan [73], 1991; Gong and Zhao [74], 2007; Jin [77] (2014)), and there is also a possibility for predicting rock burst [78–81].

B_1 and B_2 are simple indices to attain, and their simplicity makes them preferred by researchers and engineers. Nevertheless, there are limitations to the indices, for example, the rock fracture process is not reflected in the physical meaning of the two indices. Thus, B_1 is more appropriate to define rock strength than brittleness. Rocks with different σ_c and σ_t values may have the same B_1 value with a narrow difference range, which limits its

effectiveness as a brittleness index [33]. Strength brittleness indices quantify a material's fracture behavior by evaluating strength, stress–strain characteristics, and crack initiation stress, as presented in Table 2 with their corresponding formulas and parameters.

Table 2. Summary of brittleness indices based on strength, stress–strain curve, and crack initiation stress.

Measurement Methods	Formulation	Authors	Measurement Parameter
Based on strength parameter	$B_1 = \frac{\sigma_c}{\sigma_t}$	[76]	σ_c is the uniaxial compressive strength; σ_t is the tensile strength.
	$B_2 = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)}$	[76]	
	$B_3 = \frac{\sigma_c \sigma_t}{2}$	[64]	
	$B_4 = \sqrt{\frac{\sigma_c \sigma_t}{2}}$	[64]	
Based on strength and crack initiation	$B_5 = \frac{\sigma_c}{\sigma_t} = 8 \frac{\sigma_c}{\sigma_t} = \frac{8}{K}$	[82]	σ_c is the uniaxial compressive strength; σ_t is the splitting tensile strength; and σ_i is the crack initiation stress. K is the crack initiation stress level.
	$B_6 = \frac{(\sigma_c - \sigma_t)}{(\sigma_c + \sigma_t)} = \frac{(8 - K)}{(8 + K)}$	[82]	
Based on stress–strain curve	$B_7 = \frac{(\tau_p - \tau_r)}{\tau_p}$	[83]	τ_p is the peak compressive strength; τ_r is the residual compressive strength; ε_p is the peak strain; ε_r is the residual strain; ε is the total strain; ε_f^p and ε_c^p are the plastic strains necessary for cohesion loss and frictional strengthening, respectively; W_r is recoverable strain energy; W is the total strain energy; E is the elasticity modulus of pre-peak; M is the elasticity modulus of post-peak; k_{ac} is the stress slope of post-peak; σ_p is peak stress; σ_r is residual stress; σ_p is peak strain; ε_r is residual strain ε_{BRIT} is peak strain; ε_m is the reference value of the maximum peak strain; ε_n is the reference value of the minimum peak strain; α , β , and η are standardized coefficients; σ_p is peak stress; σ_r is residual stress; ε_p is peak strain; and ε_r is residual strain.
	$B_8 = \frac{(\varepsilon_p - \varepsilon_r)}{\varepsilon_p}$	[83]	
	$B_9 = \frac{\varepsilon_r}{\varepsilon}$	[84]	
	$B_{10} = \frac{(\varepsilon_f^p - \varepsilon_c^p)}{\varepsilon_c^p}$	[85]	
	$B_{11} = \frac{W_r}{W}$	[86]	
	$B_{12} = \frac{dW_r}{dW_e} = \frac{(M - E)}{M}$	[87]	
	$B_{13} = \frac{dW_k}{dW_e} = \frac{E}{M}$	[88]	
	$B_{14} = \frac{(\tau_p - \tau_r)}{\tau_p} \cdot \frac{1}{10} k_{ac} $	[89]	
	$B_{15} = \frac{(\sigma_p - \sigma_r)}{(\varepsilon_r - \varepsilon_p)} + \frac{[(\sigma_p - \sigma_r)(\varepsilon_r - \varepsilon_p)]}{(\sigma_p \sigma_r)}$	[67]	
	$B_{16} = \frac{(\varepsilon_{BRIT} - \varepsilon_n)}{(\varepsilon_m - \varepsilon_n)} + \alpha SC_{BRIT} + \beta CS_{BRIT} + \eta, SC_{BRIT} = \frac{[\varepsilon_p(\sigma_p - \sigma_r)]}{[\sigma_p(\sigma_r - \varepsilon_p)]}$	[90]	

Brittleness indices B_3 , B_4 , and B_5 have been used to explore the relationship between rock brittleness and various factors such as drillability, sawability, and drilling rate [91]. Additionally, B_4 has been applied to different rock types, including norite, to predict fracture toughness values wherein higher B_4 values are associated with lower brittleness in rocks [63].

Torokh et al. [92] (2016) introduced B_{13} , but both B_{12} and B_{13} fail to capture the full stress–strain path, limiting their ability to represent brittle failure. Rybacki et al. [93] (2016) improved upon this with B_{15} , which considers both stress and strain, but it still neglects post-failure processes. Meng et al. [89] (2015) developed B_{16} , which accounts for both rupture strength loss and inelastic strain but ignores variations in rock behavior within the elastic region.

The study by Kivi et al. [68] (2018), as shown in Figure 11, outlines the brittleness indices based on stress or strain characteristics. Figure 11 comprise various class I stress–strain curves, showing different pre-peak and post-peak brittle characteristics. O represents the origin, O' is the point of elastic strain recovery, and B is the failure point. A and A' are

the yield points for two distinct pre-peak deformation behaviors. BE illustrates a completely brittle failure path, BF represents a perfectly plastic path, and BC, BCO, and BD depict various semi-brittle failure paths.

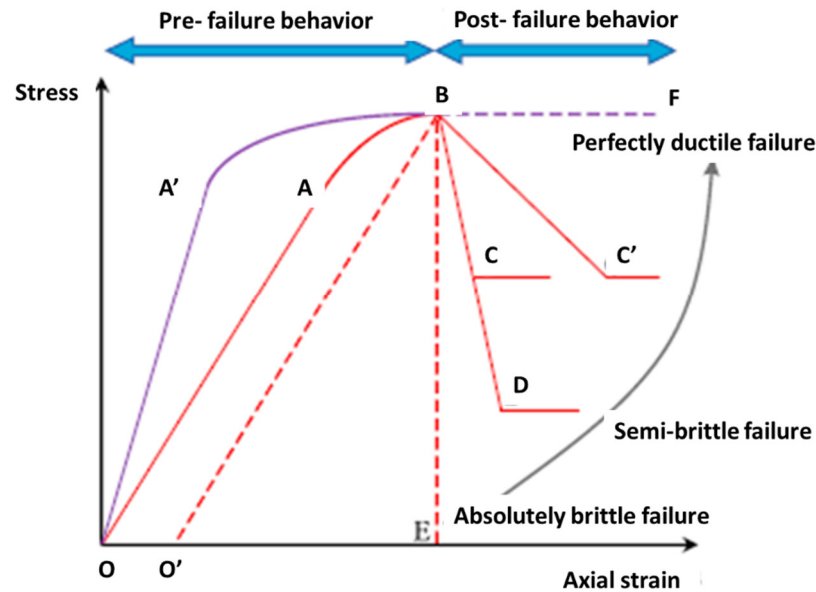


Figure 11. A schematic diagram showing the behavior of the material when under conditions of stress and strain [68].

The brittleness of norite is strongly influenced by petrographic factors such as the grain area ratio (GAR), cement and matrix contents, packing density (Pd), packing proximity (Pp), concavo-convex structure, feldspar percentage, and long and tangential contacts [27]. The mechanical properties of rock masses are associated with these petrographic characteristics [27]. Petrographic characteristics also include the average mineral size and their mineralogical composition [28]. Minerals play a crucial role in determining the brittle and ductile behavior of rocks from a structural perspective. It is commonly believed that rocks containing strong or brittle minerals are more likely to exhibit brittle characteristics, while those with a higher proportion of weak or ductile minerals tend to show less brittleness [94].

Brittleness indices B_{48} to B_{54} are primarily based on mineral compositions, representing the ratios of minerals that contribute to brittle failure. In contrast, indices B_1 to B_{47} focus more on mechanical parameters. This suggests that mineralogical compositions alone are insufficient for accurately estimating rock brittleness, and it is essential to consider other rock fabric properties and environmental factors [68]. B_{48} to B_{54} indices can be determined through mineralogical logging tools or laboratory X-ray diffraction (XRD) analysis [66]. B_{48} , B_{49} , and B_{50} are expressed as

$$B_{48} = \frac{W_{qtz}}{W_{qtz} + W_{carb} + W_{clay}} \quad (6)$$

$$B_{49} = \frac{W_{qtz} + W_{dol}}{W_{qtz} + W_{dol} + W_{lm} + W_{clay} + W_{toc}} \quad (7)$$

$$B_{50} = \frac{W_{qfm} + W_{cal} + W_{dol}}{W_{tot}} \quad (8)$$

where W_{qtz} , W_{carb} , W_{dol} , W_{lm} , W_{cal} , W_{clay} , W_{toc} , and W_{tot} represent the weights of quartz, carbonate minerals, dolomite, limestone, calcite, clay, total organic content, and total minerals, respectively, while W_{qfm} refers to the combined weight of quartz, feldspar, and

mica. Each mineral equally contributes to the brittleness. However, B_{48} only considers quartz as the most brittle mineral, while other indices consider other minerals to be more brittle than quartz. For example, B_{50} considers quartz, feldspar, mica, calcite, and dolomite as brittle minerals [27]. B_{48} to B_{54} are commonly used in the choice and design of hydraulic fracturing in shale gas reservoirs based on various aspects of rock composition, particularly the presence of brittle or ductile minerals. The indices suggest that brittleness is solely determined by the content of brittle minerals, but their physico-mechanical properties vary, affecting the overall brittleness of the rock.

Based on the insights from the reviewed literature, particularly studies focusing on the mineralogical influence on brittleness indices, a revised brittleness index is proposed for norite that incorporates both its mechanical properties and mineralogical composition. The index incorporates the uniaxial-compressive-strength-to-tensile-strength ratio and the orthopyroxene content, formulated as

$$B_{Norite} = a (UCS/TS) + b (Opx\%) + c \quad (9)$$

where UCS is the uniaxial compressive strength (MPa), TS is the tensile strength (MPa), Opx% is the orthopyroxene volume percentage, and a, b, and c are empirically determined constants. This approach is adapted conceptually from previous studies on rock brittleness, emphasizing the influence of both mechanical properties and mineralogical composition on brittleness behavior.

Mineralogical brittleness was initially based only on the weight fraction of quartz (Jin et al. [77] (2014)) but later included both quartz and dolomite fractions due to the observation that dolomite increases shale brittleness. Brittleness indices (B_{48} to B_{54}) based on mineral content neglect other significant factors influencing rock brittleness, including the stress state, diagenesis, pre-consolidation pressure, porosity, grain size, and the type and strength of cementing materials [94]. Since rocks undergo millions of years of geological and tectonic changes, their brittleness can differ even when their mineral composition is the same [95].

The literature reviewed in this section highlights that estimating the brittleness index of rocks like norite imposes a thorough evaluation of both mechanical and petrographic properties. Norite's brittleness index is influenced by mechanical factors such as hardness, strength, and stress response, while petrographic characteristics, including the quartz and feldspar mineral composition, also play a crucial role in determining its brittleness. In the case of norite, which contains plagioclase feldspar and pyroxenes, the brittleness index is affected by the proportion and distribution of these minerals and their mechanical properties. Additionally, factors such as the grain size, porosity, and the presence of cementing materials further contribute to the overall brittleness of the rock.

5. Comparative Analysis: Mechanical vs. Petrographic Properties

This section compares and contrasts the petrographic and mechanical characteristics of rocks. The performance of the rock under different circumstances is directly impacted by mechanical characteristics such as stress, strain, strength, and stress response. On the other hand, petrographic properties, which include mineral composition, texture, and structure, provide insights into the formation of the rock. Petrographic properties provide a deeper understanding of the mineralogical makeup of a rock, whereas mechanical properties reflect its behavior under forces. Examining and understanding both properties of a rock allow for more accurate predictions of its performance in various geological and engineering contexts.

5.1. Correlation Between Mechanical Properties and Petrographic Characteristics

The mechanical properties of rock materials are related to textural characteristics. Sun et al. [96] (2017) outline the relationship between mechanical properties and textural characteristics of rocks which have been widely studied through experimental tests. These studies often use single- and multiple-variable regression analysis to examine how mechanical properties relate to textural features [95]. Textural characteristics, such as mineral composition, grain size, shape, spatial distribution, porosity, and the presence of microcracks, significantly influence the mechanical behavior of rock materials [97].

The study by Ersoy and Waller [98] (1995) established statistical relationships between mechanical rock properties and texture. Strong correlations with certain rock types such as granite were discovered. The ratio of quartz to feldspar (QFR) was found to cause a linear rise in both uniaxial compressive strength and tensile strength [99]. Thus, rocks with a higher QFR generally exhibit higher strength values.

The relationship between mechanical properties and QFR were investigated by different researchers such as Tugrul and Zarif [100] (1999), Sousa [101] (2013), and Yusofa and Zabidia [99] (2016). These researchers focused on the linear regression relationships between mechanical properties and the QFR, using regression equations to derive a conclusion about the relations. The literature provides a few examples on linear regression, which are expressed as

$$\sigma_c = 121.02 \times QFR + 115, R^2 = 0.792 \quad (10)$$

$$\sigma_c = -437.67 \times QFR + 384.82, R^2 = 0.54 \quad (11)$$

$$\sigma_t = -0.959 \times QFR + 7.685, R^2 = 0.54 = 0.039 \quad (12)$$

where σ_c is the unconfined compressive strength in MPa, σ_t is the tensile strength in MPa, and QFR is the quartz-to-feldspar ratio.

Since the 1960s, Brace [50] has shown that rocks with finer mineral grains exhibit higher mechanical strength, suggesting that grain size plays a significant role in determining the mechanical properties of a rock. Willard and McWilliams [102] (1969) further supported this by reporting that the ultimate strength of a rock and the direction of crack propagation are influenced by factors such as mineral cleavage, microfractures, and grain boundaries. This is because finer mineral grains have smaller surface areas, and as the grain size decreases, the length-to-width ratio of microcracks also decreases [103,104].

The feldspar framework first regulates the behavior of coarse-grained plagioclase rocks, including equigranular leuconorite to leucogabbro with a fine- to medium-grained subophitic texture, supporting stress even under high-grade settings [105]. Deformation weakens rock due to grain size reduction and weaker mineral phases, such as plagioclase-porphyritic leuconorite to anorthosite, forming interconnected networks and reducing its strength during deformation [105].

Generally, petrographic features such as mineralogy, grain size, texture, porosity, and alteration significantly influence the brittleness and mechanical properties of rock materials. Rocks with fine grains, a high quartz content, and tightly interlocked textures tend to display greater strength and brittleness [106]. In contrast, rocks containing altered minerals, or those with high porosity and microcracks, often show reduced strength, lower brittleness, and increased deformability. These features impact key parameters such as the uniaxial compressive strength (UCS), tensile strength, and elastic modulus by affecting how stress is distributed and how fractures are initiated within the rock [39].

The altered minerals also influence the brittleness of a rock, and the alteration processes that occur in a rock can weaken the original minerals. For example, the transformation

of feldspar to clay minerals decreases the grain cohesion and increases the porosity and microcracking of a rock [32].

5.2. Case Studies and Experimental Results

This section presents a detailed comparative analysis of existing case studies and experimental findings that investigate the relationship between mechanical and petrographic properties in norite and similar rock types. The discussion encompasses variations in hardness, strength, stress response, and brittleness indices alongside the influence of mineral composition, grain size, and microstructural features.

The study by Sun et al. [96] (2017) explored the relationship between mineral characteristics, grain size, and the mechanical properties of rock materials, providing an introduction for new researchers in the field. The study utilized regression analysis to examine the relationship between mechanical properties and textural features. Although significant progress has been made in understanding these connections, challenges remain, such as the variability in mineral composition and the complex influence of microstructures on mechanical behavior. Regression analysis, both single and multiple, are performed on experimental data to examine the relationship between mechanical properties and textural characteristics. These textural features are influenced by factors such as mineral composition, grain size, shape, spatial distribution, porosity, and inherent microcracks.

Yusofa and Zabidia [99] (2015) investigated simple regression analysis to examine the relationship between petrographic characteristics and engineering properties using 10 granitic rock samples. The findings of the study were that the strength of the rock is influenced by the mean grain size, with strength increasing as grain size decreases. Additionally, the mineral composition plays a key role in determining rock strength; thus, a higher quartz content enhances strength, while feldspar reduces it, especially when feldspar is altered. The presence of mica minerals also weakens the rock, with a higher mica content leading to a decrease in strength. Furthermore, the weathering grade affects the strength of the rock, even in samples with smaller grain sizes.

Tugrul and Zarif [100] (1999) used simple regression analysis to examine the correlations between the petrographic features and engineering properties by means of 19 distinct granitic rock samples. The findings in this study indicate that the mean grain size significantly impacts rock strength, with strength increasing as grain size decreases. Mineralogical composition is another key factor controlling rock strength, particularly the variations in quartz and feldspar contents. These minerals have opposite effects on strength: quartz has a positive effect, while feldspar has a negative one. Furthermore, there are lower correlations between mechanical properties and petrographic parameters than there are between physical qualities and petrographic behaviors.

The study by Askaripour et al. [7] (2022) highlights the impact of mineral composition, grain size, shape, and anisotropy on rock mechanics. Variations in the quartz and feldspar contents were the primary factors influencing rock strength as both minerals significantly affect the mechanical properties of the rock. Compressive strength and crack propagation are influenced by mineral composition, such as opaque and altered minerals, with grain size also playing a crucial role in determining the mechanical properties.

The study by Petrounias et al. [107] (2022) highlights that the genesis environment of ultramafic rocks from the Veria Naousa and Gerania ophiolite complexes significantly affects their mineralogical and structural characteristics, which in turn determine their suitability as concrete aggregates. Similarly, norite, a coarse-grained mafic rock formed in deep crustal settings, shares comparable petrogenetic influences that may impact its physico-mechanical properties, suggesting it could also be a suitable aggregate material if its durability and stability meet construction requirements.

The study by Petrounias et al. [108] (2023) revealed that the microstructural characteristics of diabases, especially low alteration, few soft minerals, and preserved igneous textures, directly influence the mechanical performance and durability of concrete. Diabases from Veria–Naousa and Guevgueli showed superior results compared to those from Edessa and Cyprus. Correspondingly, norite with its coarse-grained igneous texture and typically low alteration may be used as a suitable aggregate in concrete applications since it offers comparable strength and durability.

Dong et al. [109] (2025) developed an automated technique for identifying and quantifying pore types by examining pore–matrix contact relationships. Their method enhances pore identification accuracy by precisely aligning high-resolution mineral distribution maps with secondary electron images, overcoming challenges posed by low-resolution data. While intergranular pores are often misidentified, the approach performs better with coarse-grained rocks like norite compared to finer-grained ones. Meanwhile, Gao et al. [110] (2024) tackled strong ground pressure in hard-rock mining by applying graded ground fracturing to weaken multiple rock layers. This technique lowers rock strength and breakage severity, enhancing mine safety and stability. A case study at Tashan Coal Mine demonstrated notable crack formation and decreased support resistance and damage. This method shows promise for managing ground pressure in norite formations as well.

6. Engineering and Mining Implications

This section will examine the impact of brittleness index methods in evaluating mining and engineering operations. Drillability is one of the most important factors in mining and engineering applications as it directly influences the competency and cost-efficiency of drilling operations. In mining, drillability affects the speed at which boreholes can be created for exploration, extraction, and ventilation, impacting the overall productivity of the mine.

The B_3 and B_4 tests are recognized as reliable methods for evaluating drillability [111]. Askaripour et al. [7] (2022) emphasize that a detailed examination of the mineralogy of a rock offers valuable insights that enhance traditional mechanical testing in assessing the stability of surface and underground excavations. Drillability cannot be accurately defined by a single formula based only on laboratory tests, field studies, geology, experience, or equipment design [112]. Mechanical and petrographic properties correlations can predict drilling rates, but numerical values cannot fully represent the diverse geological factors involved [113]. Yarali and Soyer [112] (2011) discovered that rock strength significantly influences drillability, suggesting indirect test methods, such as the point load test and Shore scleroscope hardness, as effective alternatives for researchers without drillability equipment.

The mechanical properties of intact rock play a vital role in mining and geotechnical engineering, serving as essential design factors for tunnels, rock foundations, and slopes [114]. Some of these characteristics are also utilized as key input parameters in rock mass classification systems. Given that rock properties vary by location, it is crucial to conduct on-site investigations, particularly for engineering applications [115]. The physical and mechanical properties of intact rocks have been instrumental in rock classification for a range of engineering uses, including slope stabilization, tunnel construction, mining support systems, mine planning, and foundation design [116,117].

Aligholi et al. [118] (2019) state that the diverse petrographic composition and structural complexity of igneous rocks result in varying engineering behaviors, which can influence tunneling, mining, slope stability, and their suitability as construction materials. Aligholi et al. [118] (2019) also highlight that the mineralogical composition of igneous rocks has a greater impact on their engineering properties than rock fabric characteristics.

Among fabric properties, size descriptors play a key role in influencing engineering behavior. Moreover, fine-grained and basic igneous rocks tend to exhibit better engineering quality and lower roughness compared to coarse-grained and acidic varieties [7].

Uniaxial compressive strength (UCS) is a fundamental engineering property used in the design and planning of civil and mining projects, including dams, excavations, and tunnels. Understanding the UCS is essential for effective project development. Although direct laboratory testing is a common method for measuring UCS, it can be costly, time-consuming, and particularly challenging for soft or highly fractured rocks [119]. The combined finite discrete element method (FDEM) is increasingly used to analyze the mechanical behavior and failure of brittle geomaterials under different loading conditions. It allows for the explicit simulation of rock fracturing, from crack formation to propagation, with the mechanical response controlled by microparameters [56].

Fathipour-Azar et al. [120] (2020) highlight that using the discrete element method (DEM) clearly models particle and block interactions to simulate rock fracture and mechanical behavior, helping to advance the analysis of scale effects, heterogeneities, and confined strength estimation. In rock engineering, the uniaxial compressive strength (UCS) and the modulus of elasticity (E) are key parameters widely used for classifying intact rocks and establishing rock failure criteria. These parameters are vital for various rock physics applications, such as geomechanical engineering for onshore and offshore projects, tunneling, dam design, rock drilling and blasting, excavation, and slope stability [121].

7. Challenges and Future Research Directions

Brittleness is a crucial rock property that significantly influences both the failure behavior of intact rock and the overall response of rock masses in tunneling and mining operations [85]. However, various authors define, interpret, and apply the concept differently.

Different brittleness indices have different limitations in describing how rocks fracture, and they are presented in this section. For example, B_1 and B_2 are more closely associated with rock strength than brittleness, making B_1 more appropriate for characterizing strength rather than brittleness. B_3 to B_5 share similar limitations to B_1 and B_2 but show relationships that are useful in drillability. B_{21} is developed for shale, but it is also not perfect as it increases with peak strain, which does not always indicate higher brittleness. B_{72} , used in crack formation studies, has challenges in measuring deformation due to its dependence on load and the complexity of separating rock volume deformation from crack deformation.

Brittleness indices mainly focus on mechanical properties like strength and hardness, not focusing on the key petrographic factors such as mineral composition, grain size, and microstructures. This can lead to inaccurate assessments as these characteristics significantly influence rock brittleness and fracture behavior [66,122]. When overlooking these petrographic factors, standard brittleness indices may misrepresent rock's true behavior, leading to errors in rock engineering, drilling, and reservoir characterization [67].

Incorporating both petrographic and mechanical data of a rock provides a more comprehensive understanding, enhances predictive accuracy, and helps resolve the brittleness and determine the complex geological conditions of a rock. Askarpour et al. [7] (2022) further outlined that combining petrographic and mechanical data offers a more accurate understanding of rock behavior. This also enhances predictions of brittleness, failure patterns, and rock performance, improving decision-making and outcomes in engineering applications like drilling, mining, and reservoir management.

Future efforts should focus on developing models and equations that account for the combined effects of textural features on mechanical properties through both experiments and numerical simulations, validating these models for rocks from various origins, and applying these insights to predict mechanical properties more accurately.

Field studies are crucial for validating laboratory findings as they provide real-world data that reflect the actual conditions of the site. It is critical to understand the phenomenon of rock burst, with an emphasis on identifying its occurrence patterns. Thus, acquiring this knowledge is vital for preventing or managing procedures in mining, tunneling, and construction projects, ultimately saving both costs and lives [123]. This information can also be used to optimize designs and develop more effective techniques for excavation, support systems, and stability assessments. Ultimately, field studies bridge the gap between theoretical research and practical applications, ensuring better decision-making and more successful project outcomes.

8. Conclusions

This study has provided a comprehensive comparative analysis of the mechanical and petrographic properties of norite and their implications for geomechanical applications. The findings emphasize that norite's strength, brittleness, and durability are influenced by both its mechanical properties, such as UCS, tensile strength, and elastic modulus, as well as its petrographic features, including grain size and mineral makeup. The compatibility of norite with various engineering applications, particularly in mining, tunneling, and construction, is determined by the interactions of these factors.

The findings of this study show that combining mechanical and petrographic data for precise rock behavior characterization is important to obtain the best results when determining the brittleness indices of norite. Despite advancements, standardizing brittleness indices remains challenging due to the dependence on mechanical testing and overlooking key petrographic influences. Future research should enhance brittleness estimation techniques by incorporating petrographic and mechanical parameters and validate laboratory findings for practical applications in real-world engineering projects. This paper emphasized the importance of norite's mechanical and petrographic properties in geomechanical applications, emphasizing the need for an extensive approach to rock characterization for enhanced safety and efficiency. The study highlights that norite's strength, brittleness, and durability are strongly influenced by its petrographic features alongside mechanical properties. A finer grain size, higher quartz content, and lower porosity enhance strength and brittleness, while altered feldspar contents weaken the rock. Mineral alteration and increased porosity reduce cohesion, impacting deformation behavior. Therefore, integrating petrographic data with mechanical tests is essential for accurate brittleness assessment as mechanical indices alone may overlook key textural influences.

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