MECHANICAL BEHAVIOUR OF ANISOTROPIC FOLIATED ROCKS: IMPLICATIONS FOR TUNNEL STABILITY AND DESIGN

HARKHANI, G. P.[1*] – SHAH, M. V.[1] – SHAH, A. J.[1] – SINGH, S. R.[1]

[1] *Applied Mechanics Department, Lalbhai Dalpatbhai College of Engineering, Gujarat, India.*

**Corresponding author*
e-mail: gpharkhani2[at]gmail.com

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Abstract. Understanding the mechanical behavior of anisotropic rocks is critical for the design and stability of underground structures, particularly in tunneling and deep excavation projects. This study investigates the effects of anisotropy on the strength, deformation, and failure mechanisms of foliated metamorphic rocks such as phyllite, schist, and gneiss using a combination of laboratory techniques, including triaxial compression tests, Unconfined Compressive Strength (UCS) tests, point load tests, and petrographic analysis. The results reveal a strong dependency of rock strength on bedding orientation. At 0° and 90° to foliation, rocks exhibited higher compressive strength, whereas at intermediate angles (particularly β=30°–45°), strength significantly decreased and failure became more pronounced. Triaxial testing showed that the influence of confining pressure was more effective at lower bedding angles, diminishing at steeper ones, indicating dominant anisotropic behavior. Petrographic analysis confirmed that mineral composition, particularly the presence of mica, along with microcracks and voids, plays a substantial role in weakening rock structure at certain orientations. Point load tests supported UCS findings and offered a practical means of estimating strength anisotropy. Crack propagation patterns also varied with loading angles, with brittle failure dominating at higher angles and shear failure observed along foliation planes at lower angles. This study underscores the necessity of accounting for anisotropy in geomechanical modeling and engineering design to ensure the structural integrity of subsurface constructions.

Keywords: *rock anisotropy, foliated metamorphic rocks, triaxial compression test, tunnel stability*

Introduction

A comprehensive understanding of the physical and mechanical attributes, quality, strength, deformation behavior, and failure patterns of intact rock masses is essential for the development of engineering designs that are both safe and economically viable. The anisotropic nature of rocks significantly affects the structural stability of subsurface excavations, tunneling projects, and various civil and geotechnical engineering activities (Kumar et al., 2010). This anisotropy complicates the accurate assessment of the mechanical and physical properties of rock masses. At the microscale, factors such as mineral composition, spatial distribution of grains, voids, and microcracks govern the mechanical responses of rocks, with microcracks often exerting a predominant influence (Guo et al., 2020). In tunnel construction, especially where rock anisotropy is present, ensuring the stability of the surrounding rock is paramount. The mechanical response of anisotropic rocks varies according to the alignment of mineral grains or bedding planes in relation to external stress fields (Basu et al., 2013). Foliated metamorphic rocks, such as slate, phyllite, schist, and gneiss-exhibit high degrees of anisotropy due to the alignment of minerals in specific directions. These aligned mineral structures result in inherent weak planes that arise through processes like differential stress-induced deformation and mineral recrystallization. The performance of these rocks under stress highlights the necessity of incorporating anisotropic considerations into the evaluation

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of strength parameters during engineering design. Studies have demonstrated that the strength of these rocks is highly sensitive to the orientation of the load with respect to the inherent weak planes. Understanding the directional strength variation is crucial for solving practical engineering problems such as squeezing in tunnels, the collapse of rock pillars, and slope instability (Guo et al., 2020; Samadhiya and Jain, 2003).

Literature review

A significant number of studies have explored how the orientation of schistosity in anisotropic metamorphic rocks impacts both point load strength and unconfined compressive strength (UCS). Notable contributions in this area include the works of Basu and Kamran (2010). A variety of laboratory investigations, including triaxial testing, point load assessments, and UCS tests; have yielded differing results across rock types such as gneiss (Zhou et al., 2024; Singh et al., 2019; Liu and Xu, 2015; Kahraman, 2014; Kumar et al., 2010), phyllite (Guo et al., 2020; Xu et al., 2018; Samadhiya and Jain, 2003), and schist (Acharya et al., 2021a; Basu et al., 2013; Basu and Kamran, 2010). Findings from these studies consistently show that the angle β, which defines the relationship between the direction of principal stress and the orientation of weak planes, has a considerable effect on rock strength. Generally, strength values peak when β is aligned at 0° or 90°, while intermediate angles (between 0° and 90°) often correspond with strength minima. Based on the trend of UCS against β, anisotropy can be categorized into U-shaped, shoulder-shaped, and undulating types. Foliation orientation also influences shear strength significantly, with sliding most likely to occur along the weaker planes, especially at these intermediate angles. Under confining pressure, the degree of anisotropy decreases, and a nonlinear enhancement in strength is typically observed. The lowest shear resistance usually occurs when β ranges from 30° to 45° under various confining pressures. For example, Ramamurthy observed that in phyllite, an increase in confining pressure during triaxial tests results in a decrease in cohesion while simultaneously increasing the friction angle (Zhou et al., 2024; Singh et al., 2019).

These directional mechanical behaviors, such as compressive strength, elasticity, and deformation; are largely dictated by factors like bedding planes, fractures, and the alignment of mineral grains. In tunneling applications, the varying orientations of these geological features can result in uneven stress distributions and diverse deformation patterns, thereby influencing tunnel stability. Recognizing these anisotropic responses is essential in tunnel design, as it enables engineers to anticipate failure modes and implement appropriate support systems. The present study, therefore, focuses on evaluating how different bedding angles affect rock strength, deformation characteristics, and failure patterns in tunneling environments (Kumar et al., 2010). Furthermore, research highlights the role of microcracks, temperature, and saturation levels in shaping the physical and mechanical performance of rocks. In the context of foliated rocks, anisotropy stems not only from mineralogical composition but also from their internal structural arrangement (Liu and Xu, 2015). Microscopic examinations reveal that such rocks often contain plate-like minerals, including biotite, mica, and chlorite; that are preferentially aligned. The configuration of these weak planes has a substantial influence on strength anisotropy and can be assessed using both destructive testing methods (e.g., compression, tensile, and shear tests) and non-destructive techniques (Waqas et al., 2024; Guo et al., 2020).

The microscopic characteristics of rocks, such as their mineralogical makeup, spatial distribution of constituents, internal flaws, patterns of microfractures, and the presence of intergranular and transgranular cracks; play a crucial role in governing the macroscopic failure mechanisms when subjected to external loads. In foliated metamorphic rocks, inherent planes of weakness such as schistosity and slab-like structures are formed due to the directional alignment of minerals and microcracks induced by differential stress conditions. This alignment, especially of phyllosilicate minerals, significantly affects the way damage initiates and evolves in such rocks. These minerals, which typically exhibit elongated shapes and preferential orientations, are closely associated with microcrack development, thereby reducing the overall strength of the rock mass (Singh et al., 2019; Xu et al., 2018) (*Figure 1*). Further analysis of the microstructure of foliated rocks reveals various crack formations within the rock matrix, such as directionally aligned cracks at the periphery, cracks occurring within individual grains (intragranular), and boundary cracks encircling mineral grains. The failure or deformation behavior of these rocks under compressive stress is closely related to the angle β, which represents the orientation between weak planes and the direction of the principal stress. At elevated confining pressures and temperatures, these rocks can exhibit a transition in mechanical behavior from brittle fracturing to ductile flow (Kumar et al., 2010). Under typical compressive loads, foliated rocks often demonstrate brittle behavior; however, increasing confining pressure and temperature can result in ductile deformation. The response of these rocks is further modulated by the orientation of foliation planes. Drawing on crack evolution theory, the failure process of brittle rocks generally progresses through several distinct stages: crack closure, elastic deformation, crack propagation, coalescence of cracks, and finally, peak failure. In foliated rocks, this progression is profoundly influenced by their internal microstructural attributes, the angular orientation of the weak planes, and the surrounding environmental conditions such as pressure and temperature (Zhou et al., 2024) (*Figure 2*).

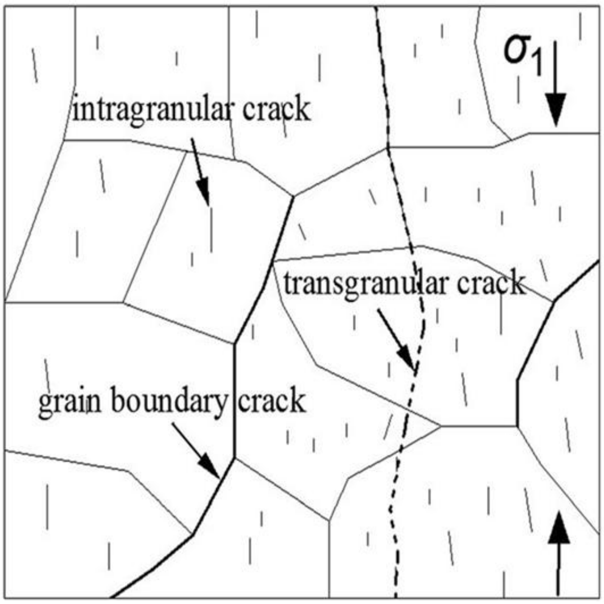

Figure 1. *Cracks in foliated rocks*
Source: Waqas et al. (2024); Yin et al. (2022).

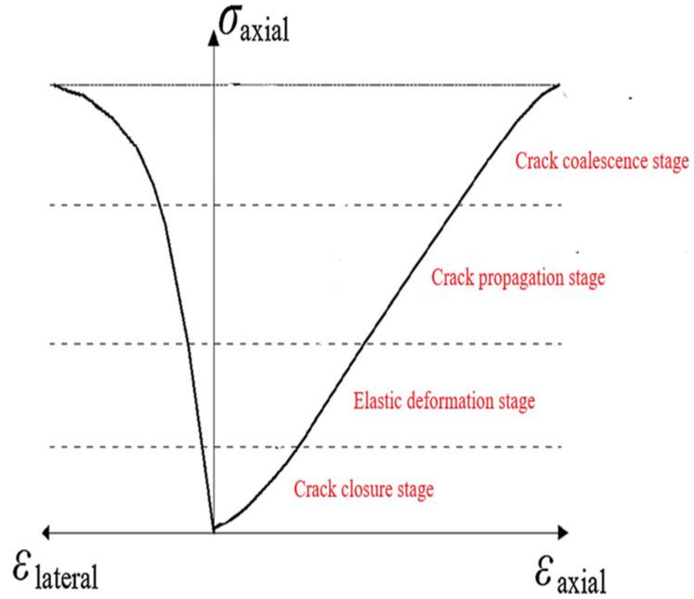

Figure 2. *Stress-Strain Behaviour and Crack Propagation.*
Source: Waqas et al. (2024).

Materials and Methods

In addition to mechanical testing, petrographic analysis was undertaken to examine the rock's mineral composition, texture, particle grading, and spatial distribution. This examination is vital for identifying how the internal fabric and mineralogical features of the rock impact its mechanical response, especially in relation to internal cracks and the presence of air voids (Dutta et al., 2021; Pandit et al., 2011). Triaxial compression testing has been extensively used to determine the strength and deformation characteristics of rocks subjected to various levels of confining pressure. These tests are particularly effective in replicating the in situ stress conditions found in deep tunnel environments, enabling better predictions of rock behavior under such conditions (Singh et al., 2019; Samadhiya and Jain, 2003). The triaxial compression test is a standardized laboratory procedure used to assess the mechanical strength of geological materials, including rocks. In this method, a uniform confining pressure (σ_3) is first applied to a cylindrical specimen, followed by the application of an axial load (σ_1). The resulting strength is referred to as triaxial compressive strength. During the test, the axial force is applied in what is termed the major principal stress direction, while the confining stress is applied in the direction of the minor principal stress. The lateral stress simulates hydrostatic pressure conditions, and the differential pressure responsible for inducing failure is known as deviator stress. For reliable test results, specimens are generally prepared with a length-to-diameter (L/D) ratio of 2 and are tested within a chamber that applies fluid pressure uniformly across all directions. This setup also allows for accurate assessment of shear strength parameters in rock materials (Guo et al., 2020; Xu et al., 2018).

Unconfined Compressive Strength (UCS) tests were also conducted on cylindrical specimens to evaluate the maximum axial load the rock can endure without lateral confinement before fracturing. This method provides crucial insights into the intrinsic strength properties of rock. Various studies have demonstrated that the peak compressive strength is typically observed when the orientation angle β is 0° or 90°, with a noticeable minimum occurring at around β=30°. Taking the compressive strength at β=90° as the benchmark, the degree of anisotropy in strength can be quantified using the anisotropy ratio Rc, calculated as σc90/σcmin (*Table 1* and *Figure 3*). To evaluate rock strength more efficiently, the point load strength test is often employed. This technique involves applying either axial or diametral loading to a rock specimen until failure occurs, thereby determining the Point Load Strength Index. This test serves as a quick and economical alternative to other mechanical strength tests and is useful in assessing the directional dependence of rock strength. While UCS testing remains the standard for many rock engineering projects, it is often time-consuming, costly, and requires precisely prepared core samples. Consequently, indirect methods, especially the point load test, are widely utilized during preliminary assessments due to their simplicity, cost-effectiveness, and adaptability for field conditions. The point load strength index (Is_{50}) is commonly used as an indirect indicator of a rock's compressive or tensile strength. Although the ISRM (Acharya et al., 2021b) recommends a UCS to Is ratio ranging from 20 to 25, numerous studies have reported a broader range of UCS/Is values, suggesting variability depending on rock type and testing conditions (Kahraman, 2014) (*Table 2*).

Table 1*. Anisotropy ratio to identify the rock anisotropy.*

Anisotropy Ratio (Rc)	Class
1.0-1.1	Isotropic
1.1-2.0	Low anisotropy
2.0-4.0	Medium anisotropy
4.0-6.0	High anisotropy
>6.0	Very high anisotropy

Table 2*. Correlation between UCS and point load strength index.*

Past study	Equation
D'Andrea et al. (1964)	$UCS = 15.3I_{s50} + 16.3$
Deere and Miller (1966)	$UCS = 20.7I_{s50} + 29.6$
Bieniawski (1975)	$UCS = 23I_{s50}$
Al-Jassar and Hawkins (1979)	$UCS = 17....30I_{s50}$
ISRM (1985)	$UCS = 20....25I_{s50}$
Quane and Russell (2003)	
Strong rocks	$UCS = 24.4I_{s50}$
Weak rocks	$UCS = 3.86 (I_{s50})^2 + 5.65I_{s50}$
Kahraman et al. (2005)	
Porosity < 1%	$UCS = 24.83I_{s50} - 39.64$
Porosity > 1%	$UCS = 10.22I_{s50} + 24.31$
Sabatakakis et al. (2008)	
$I_s < 2$ MPa	$UCS = 13I_{s50}$
$I_s = 2–5$ MPa	$UCS = 24I_{s50}$
$I_s > 5$ MPa	$UCS = 28I_{s50}$
Basu and Kamran (2010)	$UCS = 11.218I_{s50} + 4.008$
Kohno and Maeda (2012)	$UCS = 16.4I_{s50}$

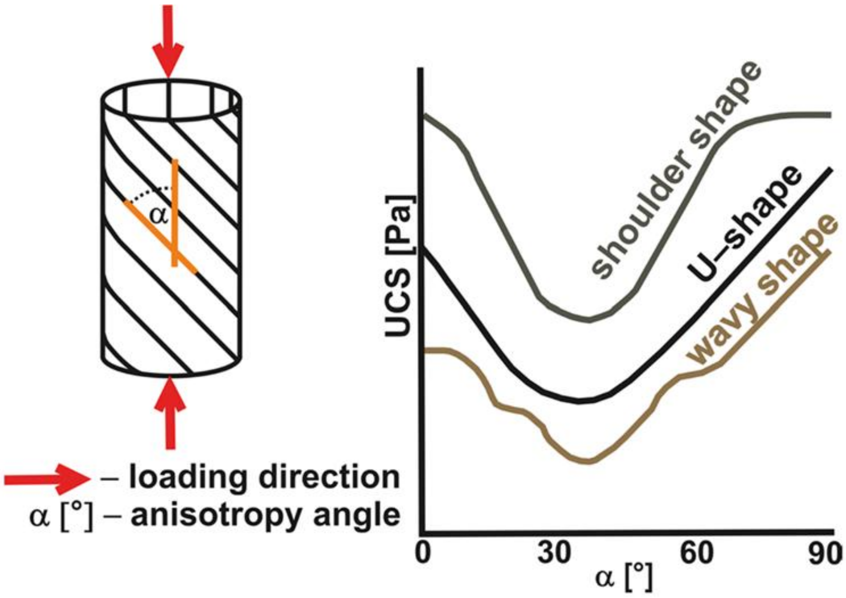

Figure 3. *Curves of strength anisotropy.*

Results and Discussion

The outcomes of the triaxial, unconfined compressive strength (UCS), and point load tests clearly demonstrated that the strength and deformation behavior of the rock varied depending on the bedding angle. When the loading direction was aligned parallel to the foliation planes (0°), the rock displayed higher compressive strength and experienced minimal deformation. This suggests that the foliation provided structural reinforcement against failure. As the bedding angle increased, a decline in rock strength was observed, with the most significant reduction noted at 90°, where the loading was perpendicular to the foliation. Under triaxial conditions, it was evident that confining pressure significantly influenced strength at lower bedding angles, leading to notable strength enhancement. In contrast, at higher bedding orientations, the effect of confinement was less pronounced, indicating that anisotropic properties were the primary factor influencing the rock's mechanical response (*Table 3*).

Table 3*. Tests result of different rock.*

Rock type	Triaxial test (MPa)	UCS test (MPa)	Point load test (MPa)	Reference
Phyllite	102.32	45.73	1.55	Samadhiya and Jain (2003)
Marble	-	57.3	3.95	Kahraman and Gunaydin (2009)
Quartzite	-	111.5	8.7	
Gneiss	-	85.9	4.7	
Migmatite	-	203.6	13.3	
Limestone	-	127.25	6.25	
Schist	-	77.43	3.58	Basu and Kamran (2010)
Biotite gneiss	34.95	-	-	Kumar et al. (2010)
Augen gneiss Quartzite	54.6	-	-	
Biotite chlorite schist	97.41	-	-	
	60	-	-	
Gneiss	-	-	2.3	Sabatakakis et al. (2008)
Weathered gneiss	-	-	0.6	
Schist	-	-	2.2	
Limestone	-	-	2.45	
Granite	-	124.98	8.9	Basu et al. (2013)
Schist	-	58.25	3.8	

Sandstone	-	43.62	4.79	
Pyroclastic rocks				Kahraman (2014)
Dry	-	24.45	1.75	
Saturated	-	18.15	1.18	
Granite gneiss	145	-	-	Liu and Xu (2015)
Shale	-	9.15	0.45	Alitalesh et al. (2016)
marlstone		36.5	4.65	
Phyllite	70.15	-	-	Xu et al. (2018)
Migmatic gneiss	143.98	45.9	-	Singh et al. (2019)
Quartzitic phyllite	171.7	83.38		
Phyllitic quartzite	178.68	97.81		
Chlorite phyllite	40.5	-	-	Guo et al. (2020)
Sericite phyllite	12.5	-	-	
Quartz phyllite	27	-	-	
Carbonaceous phyllite	127.33	-	-	Fu et al. (2023)
Gneiss granite	124.6	-	-	Zhou et al. (2024)
Augen gneiss	-	50	2.9	Acharya et al. (2021b)
Granitic gneiss	-	62.5	4.5	
Schist	-	46.5	2.2	

The modes of failure recorded during testing were consistent with the known characteristics of anisotropic rock materials. When the bedding angle ranged between 0° and 45°, the rock primarily failed along foliation planes, exhibiting typical shear failure. In comparison, at steeper angles of 60° and 90°, the failure became increasingly brittle, resulting in more fragmented and unpredictable fracture patterns. These findings underscore the critical role of bedding plane orientation in anticipating failure mechanisms, especially in tunneling and underground excavation projects (*Figure 4*). Petrographic evaluations further supported these mechanical observations by revealing noticeable compositional differences in the phyllite samples. The mineralogical structure was predominantly composed of quartz, feldspar, and mica. Among these, mica played a crucial role in deformation behavior due to its function as a plane of weakness within the rock. Moreover, internal microcracks and air voids, features more frequently found in samples tested at higher bedding angles, also contributed to the overall decrease in strength at those orientations.

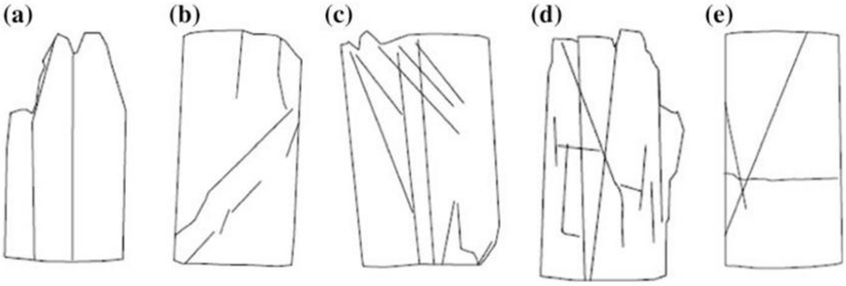

Figure 4. *Failure patterns observed under unconfined and triaxial conditions: (a) axial splitting, (b) shearing along plane, (c) axial splitting with shearing, (d) multiple fracturing and (e) along foliation.*
Source: Singh et al. (2019).

Conclusion

The present study highlights the critical impact of anisotropy on the mechanical performance of foliated metamorphic rocks, offering significant implications for geotechnical engineering, particularly in tunneling and underground construction. Through a comprehensive experimental framework, including triaxial compression, UCS, point load tests, and petrographic evaluations, it was established that rock strength and failure modes are strongly influenced by the orientation of foliation planes relative to the direction of applied stress. Key findings indicate that rocks tested parallel (0°) or perpendicular (90°) to foliation planes exhibited higher strength and lower deformation. In contrast, rocks oriented at intermediate angles (especially between 30°–45°) demonstrated notable strength reduction and higher failure potential. Triaxial testing confirmed that while confining pressure enhances rock strength, its effect diminishes at steep foliation angles due to the overriding influence of inherent anisotropy. These mechanical trends align with observed failure patterns, ranging from shear along foliation planes at low angles to brittle fracturing at high angles. Petrographic analysis provided further insights into the role of mineralogical features, especially mica content, in governing rock deformation. The prevalence of microcracks and air voids, particularly in higher bedding orientations, exacerbated strength losses and instability. Moreover, the correlation between UCS and point load strength index supports the feasibility of using indirect tests for rapid field assessments of anisotropic rock behavior. Overall, the findings of this study emphasize the importance of incorporating anisotropic considerations into design models and safety evaluations. By improving predictions of rock mass behavior under various loading and bedding orientations, engineers can better tailor support systems and optimize excavation techniques for complex geological settings.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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