

# Relationship between UCS and Anisotropic Angle: A Case Study for Slate of Himalaya Region

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**Abstract:** *The strength of rocks exhibits anisotropy because of their mode of formation and their development through different pressure and temperature environments. A rock can display anisotropy due to inhomogeneity, where the sedimentary layers vary with the degree of the anisotropic plane. This "strength anisotropy" refers to the change in intact rock strength under uniaxial loading conditions based on the orientation of anisotropy. The strength and deformation behaviour of rocks under load is critical for underground excavations, mining, and civil engineering projects, as it directly impacts the stability of such structures. This study examines the strength index, which is influenced by the anisotropic plane at different loading angles. The rock material, characterised by layers developed from platy minerals with sometimes varying grain sizes, shows that an increase in foliation degree to loading angle directly impacts its strength. In slate, the strength index is influenced by the anisotropic plane and loading direction, which are also controlled by the characteristics of mineral grains. This study aims to enhance the existing understanding of this behaviour by analysing the uniaxial compressive strength (UCS) of anisotropic, low-grade metamorphic rock.*

**Keywords:** UCS, Strength, Anisotropy.

## I. INTRODUCTION

In nature, most rocks exhibit anisotropy due to their mode of formation and development through different pressure and temperature environments. A rock or rock mass can display anisotropy due to inhomogeneity, where sedimentary strata exhibit varying properties depending on whether the direction is parallel or perpendicular to the layering. Variations in strength and anisotropy trends are linked to the mineral content within the rock. The different types of mineral aggregates and their shapes significantly impact the mechanical behaviour of the rock. When rocks undergo heating and cooling, changes in their physical properties occur due to the presence of various minerals within them. The development of anisotropy in rocks causes changes in their strength in different directions, which is referred to as strength anisotropy in stones.

In metamorphic rocks, anisotropy is often caused by past stress, which aligns mineral grains in bands or preferred orientations [1]. The variation in strength in the rock makes it essential to estimate its strength anisotropy, which is determined by the ratio of maximum to minimum strength in the rock [2]. Strength anisotropy in rocks can be measured by applying loads at different angles relative to the anisotropic plane. Stress-induced foliation is influenced by the type of minerals present in the rock, such as slate or gneiss, which may possess inherent anisotropy from their formation process. In such anisotropic stones, the rock is influenced by the direction of the applied stress; these anisotropic properties affect both the physical and mechanical behaviour of the rock, influencing its strength and controlling how fractures initiate and propagate. Anisotropic rocks show varying deformability modulus, strength, brittleness, permeability, and discontinuity frequency in different directions [3]. Therefore, measuring rock strength is crucial for the design of engineering structures, underground excavations, and other construction projects, as it directly influences the stability of these works.

The direction of the applied stress influences the strength of a rock. A rock or rock mass can display anisotropy due to inhomogeneity, where sedimentary strata exhibit varying properties depending on whether the direction is parallel or perpendicular to the layering. In metamorphic rocks, anisotropy is often caused by past stress, which aligns mineral grains in bands or preferred orientations [2]. Stress-induced foliation is influenced by the type of minerals present in the rock, such as slate or gneiss, which may possess inherent anisotropy from their formation process. Anisotropic rocks show varying deformability modulus, strength, brittleness, permeability, and discontinuity frequency in different directions [3]. These anisotropic properties affect both the physical and mechanical behaviour of the rock, influencing its strength and controlling the initiation and propagation of fractures.

Among the several strength parameters, the uniaxial compressive strength is a commonly used parameter for assessing the strength of intact rock in engineering applications [4]. The degree of strength anisotropy was grouped, and classification was proposed [5]. The primary objective of this research is to assess the rock strength under varying loading angles. Understanding the strength and behaviour of these rocks can help estimate their suitability for engineering construction and design. Experimental data have been used to establish empirical and graphical relationships for predicting the uniaxial compressive strength (UCS) failure behaviour of anisotropic rocks under different loading angles. This study aims to enhance the existing

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knowledge base and provide valuable insights into the failure behavior of anisotropic rocks.

## II. METHODOLOGY

Samples of slates were collected from different places in Central Nepal for laboratory analysis. In the lab, the samples underwent preparation, including core cutting, surface smoothing, and testing. The key laboratory test performed was the Uniaxial Compressive Strength Test at room temperature. Samples were prepared with varying loading angles, labelled, and subsequently tested. Samples were tested at room temperature. Cylindrical core samples of slate were loaded in the Uniaxial direction in varying anisotropy angles of 0°, 30°, 45°, 60°, 75°, and 90°. Three sets of tests were conducted with different anisotropic angles, and the results obtained are presented in the tables. The methodology followed the guidelines set by the ISRM (1985).



[Photograph 1: Sample Preparation of Selected Slate Specimens for the UCS Tests]



[Photograph 2: Core Samples Prepared at Lab on Different Foliation Angle]

## III. RESULTS

The observed results are grouped into two sections. One result examines the variation pattern of strengths in the rock, and the second investigates the correlation between strength and loading angle.

### A. Determination of Uniaxial Compressive Strength

In the uniaxial compressive strength test, applying stress in different loading orientations led to variations in the strength

of intact rock. The extent of these strength changes reflects the level of anisotropy within the rock.

Table 1: UCS Value of Slate at Different Anisotropy Angles

Anisotropy Angle	UCS (MPa)		
	First Series	Second Series	Third Series
B (°)			
0	107.7	112.2	69.22
30	64.11	57.65	42.42
45	46.52	33.72	26.47
60	77.81	61.1	52.7
75	91.2	81.2	52.24
90	132.9	115.2	130.9

The graph demonstrates the relationship between the orientation of the weak planes and the corresponding change in strength. Anisotropic behaviour was observed in each test at different orientations, with the rock achieving its maximum strength at  $\beta = 90^\circ$  and its minimum strength at  $\beta = 45^\circ$ . The strength initially decreased for samples tested at  $0^\circ$ , then decreased slightly as the anisotropic angle increased to  $30^\circ$ , reached its minimum value at  $45^\circ$ , rose again at  $60^\circ$ , and finally peaked at  $90^\circ$ . The strength showed a slight reduction (1–2 times on average) for samples tested at  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ , but a significant increase was observed at  $75^\circ$  and  $90^\circ$  compared to the strength values at  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ . Overall, the UCS value for Slate increased, reaching its maximum strength.

The trend line in Figure 1, derived from the scatter plot of data across the three test series, illustrates the generalised relationship between Uniaxial Compressive Strength (UCS) and the anisotropy angle. This equation, shown alongside the graph, provides a mathematical representation of how the UCS of the material changes as the orientation of applied stress relative to the anisotropic plane varies. Table 1 likely provides supplementary quantitative data that supports this relationship, detailing specific UCS values corresponding to different angles or other relevant parameters.

The strength decreased slightly (by an average factor of 1–2 times) for samples tested at  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ . However, there was a significant increase in strength at  $75^\circ$  and  $90^\circ$  compared to the values at  $30^\circ$ ,  $45^\circ$ , and  $60^\circ$ . The strength was highest at  $0^\circ$  and  $90^\circ$  but decreased towards  $45^\circ$ , following a U-shaped pattern, as shown in Figure 1.

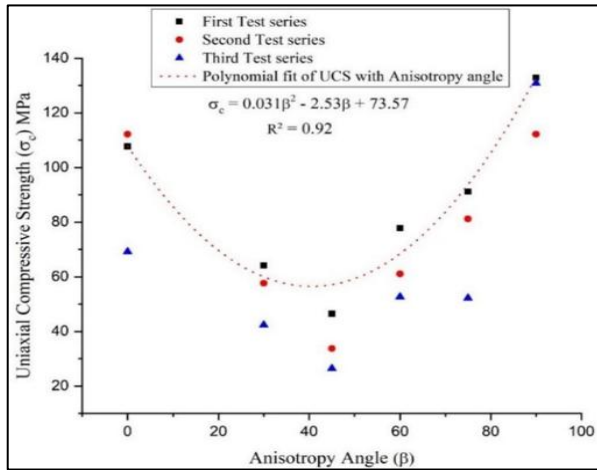
### B. Correlation of UCS ( $\sigma_c$ ) with Anisotropy Angles ( $\beta$ )

As a result, the generalized strength anisotropy equation for Slate specimens is deduced from the graph (figure 1). The analysis of the testing data has established an empirical relationship between rock strength and the anisotropy angle, which is expressed in Equation 2.

$$\sigma_c = 0.031\beta^2 - 2.53\beta + 73.57 \quad \dots \text{ (Equation 1)}$$

Where,  $\sigma_c$  = Uniaxial Compressive Strength,  
 $\beta$  = Anisotropy Angle.





[Fig.1: Scatter Plot and Trend Line from Three-Test Series and its Generalized Equation]

Based on the data presented in Table 1 and depicted in Figure 1, a polynomial relationship can be established to illustrate the correlation between compressive strength and the orientation of rock specimens. By fitting the data to a curve, the equations for these relationships can be determined. Upon examining Figure 1, it is clear that the strength gradually decreases as the loading angle increases, reaching its lowest point at 45°. However, beyond this point, the strength begins to grow, forming a U-shaped curve and exhibiting a strong positive correlation. Table 1 presents the empirical formulas that relate the compressive strength of slate rock samples to their orientation. The relationship between strength and orientation is indicated by the proportionality factor, which is determined by the slope of the fitted curve.

Therefore, the positive correlation between  $\sigma_c$  and orientation is robust, with a fitting coefficient  $R^2$  of 0.92, which exceeds 0.90. This indicates a clear polynomial relationship between  $\sigma_c$  and orientation under these conditions. Various fitting methods other than the polynomial function were tested to relate  $\sigma_c$  and  $\beta$ , but they did not yield satisfactory results. The polynomial function provided the best fit, accurately describing the relationship between  $\sigma_c$  and  $\beta$ . As a result, using this polynomial function would offer a more precise prediction of the coefficient of anisotropy. Based on the analysis, it is evident that there is a robust correlation between compressive strength and the anisotropy angle.

#### IV. DISCUSSION

The anisotropic strength behaviour of rocks can be characterised using the classification proposed by researchers who identified three distinct strength anisotropy patterns: "wavy-shaped," "U-shaped," and "shoulder-shaped." The findings of the present study align with the U-shaped anisotropy pattern, where rock strength is highest at 0° and 90° but decreases toward 45°. This observation is consistent with the research [2], titled Mechanical Properties and Failure Patterns of Migmatized Gneiss with Metamorphic Foliation under UCS Test, which reported a similar U-shaped strength distribution.

Additionally [6], the failure behavior of anisotropic rocks was analyzed in the study and [7] using the point load index test

and uniaxial compressive strength. Study of [6] found that the point load index strength of anisotropic rocks is influenced by grain size and the loading angle relative to the planes of anisotropy. Similarly, uniaxial compressive strength also varies with the degree of anisotropy. Current research demonstrates a strong correlation between compressive strength and anisotropy angles, further supporting these findings.

In another related study, [8] investigated the strength variation of augen gneiss under different loading directions and temperatures using the point load test. The results indicated that the anisotropic nature of rock strength varies with the degree of anisotropy in the plane of interest. These findings are in agreement with the results of our current research.

#### V. CONCLUSION

This study investigates the failure behavior of anisotropic rocks under Uniaxial Compressive Strength (UCS) testing. The significant findings are summarized as follows:

The compressive strength of anisotropic rocks varies significantly with the loading angle ( $\beta$ ). The maximum strength is observed when the loading direction is either perpendicular ( $\beta = 90^\circ$ ) or parallel ( $\beta = 0^\circ$ ) to the foliation plane. In comparison, the minimum strength occurs at  $\beta = 30^\circ$  in the first test series and  $\beta = 45^\circ$  in the subsequent series. Generally, strength decreases between  $\beta = 30^\circ$  and  $\beta = 45^\circ$ , then increases at  $\beta = 60^\circ$ , reaching its peak at  $\beta = 90^\circ$ . This variation illustrates the significant impact of anisotropy on the material's mechanical behaviour.

The relationship between uniaxial compressive strength ( $\sigma_c$ ) and the anisotropy angle ( $\beta$ ) for slate specimens is described by the equation:

$$\sigma_c = 0.031\beta^2 - 2.53\beta + 73.57$$

This equation provides a quantitative tool for predicting strength variations in anisotropic rocks based on their orientation to the applied load.

Failure mechanisms are highly dependent on the orientation of the anisotropic planes. When loading is parallel ( $\beta = 0^\circ$ ) or perpendicular ( $\beta = 90^\circ$ ) to the foliation, the induced stress at the tips of the planes is low, necessitating higher applied stress to initiate fractures. However, for inclined orientations ( $\beta = 30^\circ, 45^\circ, 60^\circ$ , and  $75^\circ$ ), compressive stresses are transferred to the foliation plane, generating shear forces that reduce the overall strength of the rock.

The strength variation and failure mechanisms are further influenced by factors such as the anisotropic index, grain size, and the cross-sectional area at different loading angles. These properties determine the slope and curvature of the strength versus loading angle relationship, highlighting the complex interaction between material structures and loading conditions.

#### DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/Competing Interests:** Based on my





understanding, this article does not have any conflicts of interest.

- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it was conducted without any external influence.
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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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