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

Anand Gupta, Suman Panthee, Janani Selvam

***Abstract:** The strength of rocks exhibits anisotropy, because of its mode of formation and its developing through different pressure and temperature environment. A rock can display anisotropy due to inhomogeneity, where sedimentary varying 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 behavior 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, characterized by layers developed by platy minerals with sometime 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 characters of mineral grains. This study seeks to enhance the existing understanding of this behavior by analyzing uniaxial compressive strength (UCS) performed on anisotropic low grade metamorphic rock.*

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

I. INTRODUCTION

In nature, most rocks exhibit anisotropy, because of its mode of formation and its developing through different pressure and temperature environment. 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. Different types of mineral aggregates and their shapes affect the mechanical behavior of the rock. When rocks undergo heating and cooling, changes in their physical properties occur due to the presence of various minerals. The developed anisotropy in rocks causing changing its strength in different direction which is called strength anisotropy in rock [9].

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*Correspondence Author(s)

Anand Gupta, Faculty of Engineering, Lincoln University College, Malaysia. Email ID: agupta@lincoln.edu.my, ORCID ID: 0009-0000-8338-7447

Suman Panthee*, Central Department of Geology, Tribhuvan University, Nepal. Email ID: sumanpanthee@gmail.com, ORCID ID: 0009-0001-5617-6721

Dr. Janani Selvam, Faculty of Engineering, Lincoln University College, Malaysia. Email ID: janani@lincoln.edu.my, ORCID ID: 0000-0002-1041-9003

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 making it essential to estimate their 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 place. 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 rocks, the rock influenced by the direction of the applied stress, these anisotropic properties affect both the physical and mechanical behavior 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 strength of a rock is influenced by the direction of the applied stress. 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 behavior of the rock, influencing its strength and controlling how fractures initiate and propagate.

Among the several strength parameters, the uniaxial compressive strength is commonly used strength parameter of an intact rock in engineering application [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 behavior of these rocks can aid in estimating their suitability for engineering construction and design [10]. Experimental data have been used to establish empirical and graphical relationships for predicting uniaxial compressive strength (UCS) failure behavior under different loading angles in anisotropic rocks [11]. This study aims to enhance the existing knowledge base and provide valuable insights into the failure behavior of anisotropic rocks.

II. METHODOLOGY

Samples of slates were collected form the different places of 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 different loading angles, labeled, and tested. Samples at the room temperature were tested. Cylindrical core samples of slate were loaded in the Uniaxial direction in varying anisotropy angles 0º 30º 45º 60º 75º and 90º. Three sets of tests were carried out with different anisotropic angle and the obtained results are shown 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 deals with the variation pattern of the strengths in the rock and second deals with 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)		
B (˚)	First Series	Second Series	Third Series
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 behavior was observed in each test at different orientations, with the rock achieving maximum strength at β = 90º and minimum strength at β = 45º. The strength initially decreased for samples tested at 0º, slightly decreased as the anisotropic angle increased to 30º, reached its minimum value at 45º, then rose again at 60º, and finally peaked at 90º. The strength showed a small reduction (1–2 times on average) for samples tested at 30º, 45º, and 60º, but a significant increase was observed at 75º and 90º compared to the strength values at 30º, 45º, and 60º. 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 generalized relationship between Uniaxial Compressive Strength (UCS) and 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 30º, 45º, and 60º. However, there was a significant increase in strength at 75º and 90º compared to the values at 30º, 45º, and 60º. The strength was highest at 0º and 90º but decreased towards 45º, following a U-shaped pattern, as shown in Figure 1.

B. Correlation of UCS (σc) with Anisotropy Angles (β)

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 anisotropy angle which is expressed in the following Equation 2.

$$\sigma c = 0.031\beta 2 - 2.53\ \beta + 73.57 \quad \ldots \quad \text{(Equation 1)}$$

Where, σc = Uniaxial Compressive Strength,

β= Anisotropy Angle.

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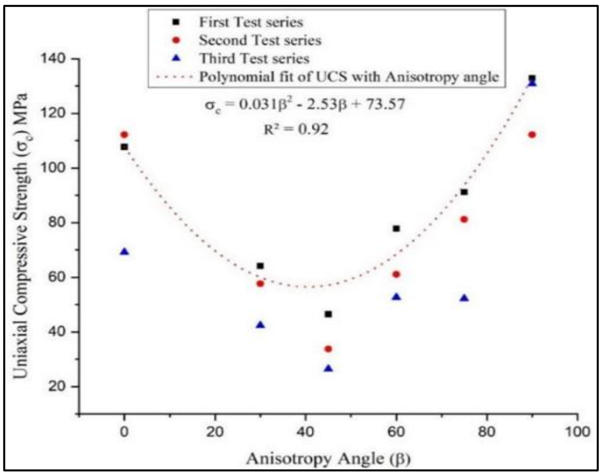

[Fig.1: Scatter Plot and Trend Line from Three-Test Series and its Generalized Equation]

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 45º. However, beyond this point, the strength begins to increase, forming a U-shaped curve and exhibiting a strong positive correlation. Table 1 provides the empirical formulas that connect compressive strength with the orientation of slate rock samples. 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 σ_x and orientation is very strong, with a fitting coefficient R2 of 0.92, which exceeds 0.90. This indicates a clear polynomial relationship between σ_x and orientation under these conditions. Various fitting methods other than the polynomial function were tested to relate σ_x and β, but they did not yield satisfactory results. The polynomial function provided the best fit, accurately describing the relationship between σ_x and β. 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 behavior of rocks can be characterized using the classification proposed 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 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. 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 major findings are summarized as follows:

The compressive strength of anisotropic rocks varies significantly with the loading angle (β). The maximum strength is observed when the loading direction is either perpendicular (β = 90°) or parallel (β = 0°) to the foliation plane, while the minimum strength occurs at β = 30° in the first test series and β = 45° in the subsequent series. Generally, strength decreases between β = 30° and β = 45°, then increases at β = 60°, reaching its peak at β = 90°. This variation demonstrates the critical influence of anisotropy on the mechanical behavior of the material.

The relationship between uniaxial compressive strength (σc) and the anisotropy angle (β) 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 (β = 0°) or perpendicular (β = 90°) 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 (β = 30°, 45°, 60°, and 75°), 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.

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AUTHOR'S PROFILE

Anand Gupta, Research Scholar in Lincoln University College, Malaysia as well as Geotechnical Engineer in N.S. Engineering & Geotechnical Services P. Ltd. He has completed Masters in Geotechnical Engineering from Institute of Engineering, Pulchowk Campus, Tribhuvan University in 2010. His area of research is experimental rock mechanics. He has good expertise in Material Testing, Pile Testing & Rock Mechanical Test.

Suman Panthee is a faculty in Central Department of Geology, Tribhuvan University, Nepal. Completed Master's Degree from Tribhuvan University and Ph.D. from IIT Bombay, India. He has more than 18 years of teaching experiences in rock mechanics, rock slope engineering, tunneling and engineering Geology and more than 6 years' experiences in the field of rock mechanics, tunneling and underground excavation and support design, and solving problems of unpredictable ground conditions in underground excavation.

Dr. Janani Selvam, Professor, Faculty of Engineering. Lincoln University College, Malaysia. She has completed Ph.D., in (Civil Engineering) 2020 Anna University, Chennai, Tamil Nadu, India. She has completed M.E., in (Structural Engineering) 2010 M.P.N.M.J Engineering College, Anna University, Coimbatore, Tamil Nadu, India. She has completed B.E. in Civil Engineering from Kongu Engineering College, Perundurai, Tamil Nadu, India. She has 11 plus years' Academic experience and 7 plus years' experience in Industry.