Anisotropic strength behaviour of slates in the Sirjan-Sanandaj zone

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Transaction Paper

Synopsis

The mechanical behaviour of schistose sedimentary rocks such as slate show a great amount of anisotropy. Hence, the schistocity plane is essential when investigating the mechanical behaviour of such rocks. The presence of such rocks in civil projects causes non-symmetric deformation and their behaviour is unpredictable. In this research, the anisotropic strength behaviour of slates is studied. Uniaxial and triaxial tests were conducted on specimens having orientation angles (β) of 0, 30, 45, 60, 75 and 90 degrees. The triaxial tests were done at confining pressures of 3, 5 and 10 MPa. The effect of anisotropy on uniaxial and triaxial strength, cohesion, angle of internal friction and Hoek and Brown's m and s constants were investigated. The results indicate that the strength of slates in uniaxial and triaxial compression exhibit a U-shaped anisotropic behaviour. In-order to evaluate the most suitable criterion for predicting the anisotropic strength of rocks in uniaxial and triaxial compression, an investigation was carried out on various criteria. In uniaxial compression, the Liao and Huong and Ramamurthy criteria had good agreements with the test results. In triaxial compression the Hoek and Brown and Mc Lamore criteria had better agreements with the test results. It should be noted that in-order to utilize these criteria, a large number of tests must be carried out. However, as the Ramamurthy criterion needs fewer test results, it can be the most suitable for investigating the behaviour of anisotropic rocks in triaxial compression.

Keywords: Slate, anisotropy, schistose, failure criteria

Introduction

Generally anisotropy is one of the factors that effect the behaviour of rocks. The properties of such rocks vary with direction. In general, rocks have some degrees of anisotropy and isotropic rocks are rarely found in nature (Kwasniewski, 1993). The rock anisotropy is mainly due to the presence of foliation, cleavage, schistosity, joints, micro and macro fissures and bedding plane (Al-Harti, 1998).

Igneous rocks are more isotropic in nature than sedimentary and metamorphic rocks (Ramamurthy, 1993, 1993), whereas metamorphic rocks are mostly anisotropic. Rocks such as slates, shales, phyllites and gneisses have anisotropic behaviour.

The direction of minerals such as chlorite and mica under the influence of tectonic stresses is one of the main reasons for presence of foliation and schistocity in the such rocks (Nasseri and Ramamurthy, 2003).

Many researchers have studied the anisotropic behaviour of rocks such as shales, slates, sandstones, geneisses, phyllites, etc. They are mainly Donath, 1964, Chenvert and Gatline, 1965, Mclamore and Garry, 1967, Hoek, 1968, Attewel and Sandford, 1974, Brown *et al.*, 1977, Deklotz *et al.*, 1966, Akai *et al.*, 1970, McCabe and Koerner, 1975, Nasseri *et al.*, 1996, 1997, Sing *et al.*, 2001, Ramamurthy, 1993, Ramamurthy *et al.*, 1988, Horino and Ellicsone, 1970, Rao *et al.*, 1986, Al-Harthi, 1998, Pomeroy *et al.*, 1971, Allirot and Boehler, 1970, and Tien and Tsao 2000. The review of these studies show that the minimum strength value is at an orientation angle of $\beta = 30°$ and the maximum failure strength is either at $\beta = 0°$ or $\beta = 90°$.

The shape of the curve between the major principal stress σ_1 and orientation angle β shows the type of anisotropy. Generally, there are three types of anisotropy, namely U-shaped, shoulder shaped and wavy shaped.

The main objectives of the present investigation are to study the anisotropic uniaxial and triaxial strength behaviour of slates in the Sirjan-Sanandaj zone in Iran. In this zone many projects such as tunnels, caverns and underground power houses for mining, dams and water conveyance are under construction. Hence, the determination of anisotropic strength behaviour of slates in this zone is essential for design purposes. The research work is also aimed at evaluating the applica-

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bility of various criteria to predict the anisotropic strength values. The slates were obtained from various project sites in the western part of Iran.

Experimental investigation

The slate that was studied is in the Sirjan-Sanandaj zone, which has special geological features. This zone, which is part of central Iran, is within the Zagros thrust zone. In order to investigate the anisotropic behaviour of slates in the Sirjan-Sanandaj zone, laboratory tests were conducted according to ISRM standards (Brown, 1981). The slate has a schistose plane of weakness. Hence, many samples were cored and prepared at different orientation angles β (0°, 30°, 45°, 60° and 90°) with regard to the schistose plane. Then laboratory investigations were carried out on these samples in order to determine the anisotropic uniaxial and triaxial strength behaviour of the slate.

Uniaxial compression test

In-order to determine the uniaxial compressive strength of slate, laboratory tests were carried out in accordance with ISRM standards on cylindrical samples at various orientation angles. The tests were carried out on orientation angles, β (the angle between the major principal stress direction and schistose plane), of 0°, 30°, 45°, 60* and 90°. Figure 1 shows the orientation angles of the tested samples. Figure 2 shows the variation of uniaxial compressive strength versus orientation angles. The results are based on the average experimental data obtained from three to five tests for each orientation. The results clearly show that the slate has a U-shaped anisotropy. The slate has the highest strength of 95.79 MPa at 90° and lowest strength of 10.32 MPa at 30°. Hence the anisotropy ratio for this slate is found to be as follows:

$$R_c = \frac{\sigma_{c\max}}{\sigma_{c\min}} = \frac{95.79}{10.28} = 9.32$$

where R_c is anisotropy ratio, $\sigma_{c\max}$ is maximum strength and $\sigma_{c\min}$ is minimum strength. Hence an anisotropy ratio of 9.32 indicates that the slate can be classified as high foliation rocks.

In order to evaluate the most suitable criterion for predicting the anisotropic strength of rocks in uniaxial compression, the Liao and Huong (Liao and Hsieh, 1999) and Ramamurthy criteria (Ramamurthy, 1993) were studied. The predicted values were then plotted and compared with experimental test results. Figire 2 shows these curves. The study clearly shows that both criteria have good agreements with the test results; however, the Liao and Huong criterion predicts the strength more precisely.

Triaxial compression test

In order to investigate the anisotropic strength behaviour of slates in triaxial compression, tests were conducted on samples having orientation angles of 0, 30, 45, 60 and 90 degrees per ISRM test procedure (Brown, 1981). Tests were done at confining pressures of 3, 5, and 10 MPa. The specimens were first subjected to the required confining pressure and then the axial load was applied until the specimen failed. Figure 3 shows the strength variations with orientation angles at various confining pressures. The plots are drawn by taking the average experimental results of three to five tests. It is clear from the results that the maximum and minimum strengths values are observed at $\beta = 90°$ and 30° respectively.

From the triaxial test results the cohesion, angles of internal friction and the Hoek and Brown m and s constants were calculated. They were then plotted against orientation angles for various confining pressures. The plots are shown in Figures 4–7.

In order to investigate the most suitable criterion for predicting the anisotropic strength of rocks in triaxial compression, various criteria was used. The most commonly criteria utilized in this study were Donath and Mclamore (Mclamore and Gray, 1967; Fahimifar and Soroush, 2003;

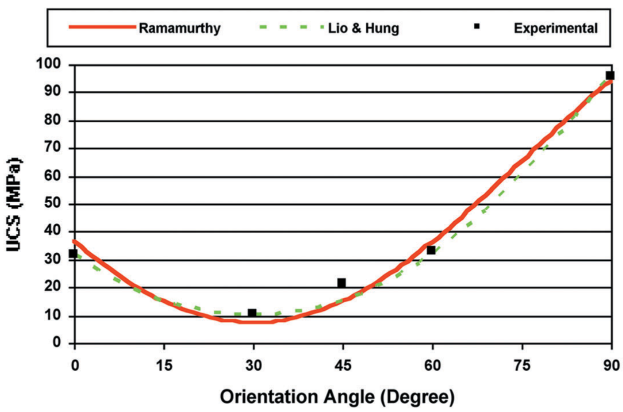

Figure 2—Experimental and predicted curves of uniaxial compressive strength of slates

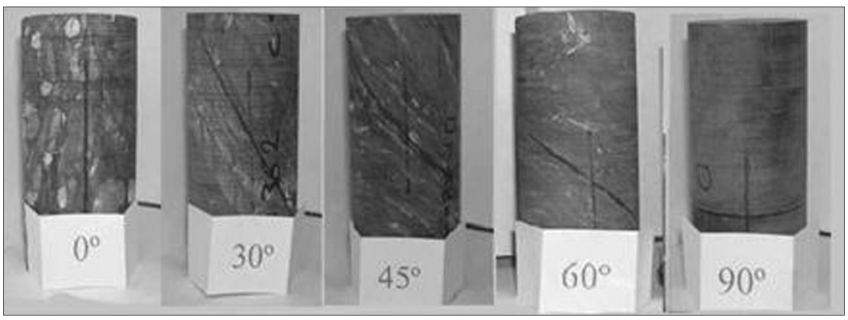

Figure 1—Orientation angles of tested slate specimens

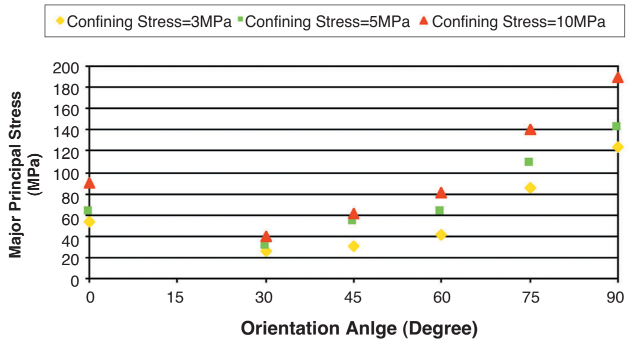

Figure 3—Variation of strengths versus orientation angles

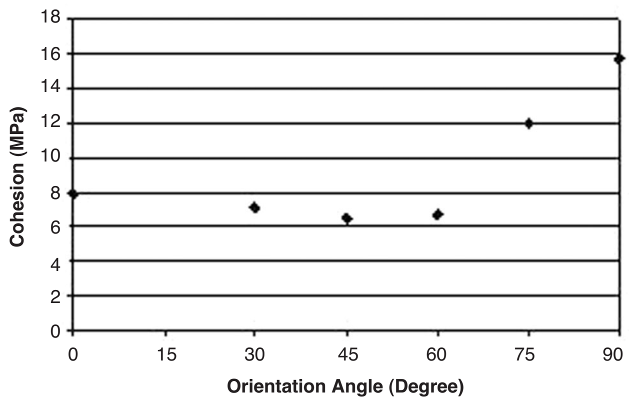

Figure 4—Variation of cohesions versus orientation angles

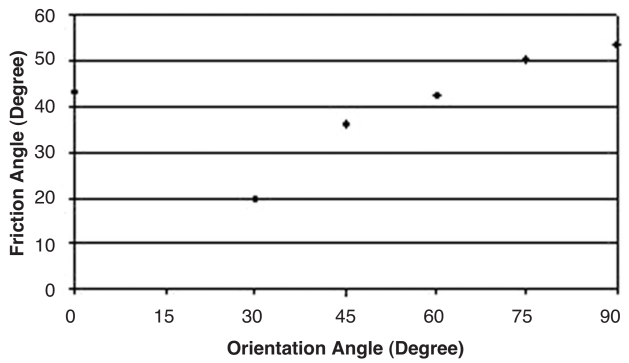

Figure 5—Variation of internal friction angle versus orientation angles

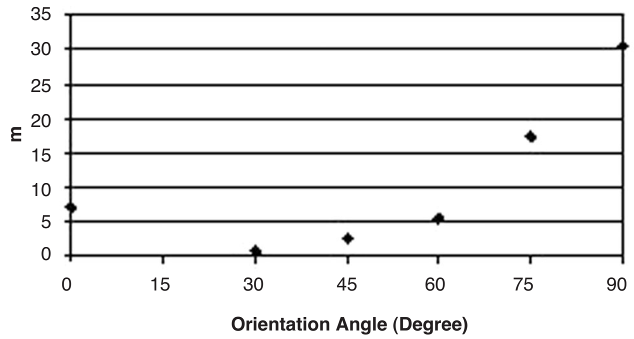

Figure 6—Variation of constant m versus orientation angles

Goodman, 1989), Hoek and Brown criterion for anisotropic rocks (Hoek and Brown, 1980), Liao & Huong (Liao and Hsieh, 1999), Tien and Kuo (Tien, and Kuo, 2001) and Ramamurthy (Ramamurthy, 1993; Nasseri *et al.*, 2003). The Donath and Mclamore criterion is based on determining the cohesion and angle of internal frictions of anisotropic rocks at various orientation angles. Ramamurthy criterion predicts triaxial strength on the basis of triaxial experimental data obtained for different orientations and confining pressures. Hoek and Brown in their criterion for anisotropic rocks, which is based on Griffith's crack theory, utilize equations for determining the m and s constants with regard to orientation angles. The Liao and Huong criterion uses the Hoek and Brown criterion and assumes that constant s value is equal to one. Values of compressive strength and constant m are taken from the test data obtained at different confining pressures and orientation angles.

The predicted strength values from these criteria were then plotted against orientation angles. Figures 8–10 exhibit the comparison between the predicted strength values and the experimental data at different confining pressures. In general, the predicted strength value by Hoek and Brown and Mc lamore criteria agrees better with the experimental test results. However, it should be noted that in order to use these criteria, it is essential to conduct three triaxial tests at

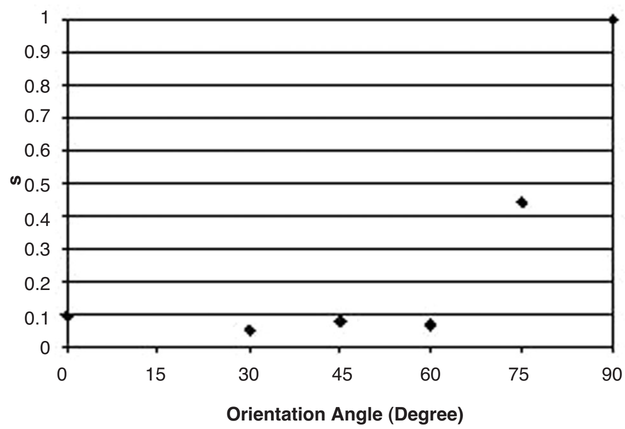

Figure 7—Variation of constant s versus orientation angles

orientation angles of 0°, 30°, 75° and 90°. In contrast, for the Ramamurthy criterion one only needs to do three uniaxial tests at orientation angles of 0°, 30° and 90° and one triaxial test in 90° at two confining pressures. Hence, it can be concluded that if very precise values are needed, then one should use the Hoek and Brown and Mc Lamore criteria by conducting a large number of tests. If the number of tests is limited, then the Ramamurthy criterion can be utilized to predict the strength values reasonably.

Conclusions

The research study on the anisotropic behaviour of slate in the Sirjan-Sanandaj zone, Iran, has yielded the following findings. The uniaxial test results show that the slate has a U-shaped anisotropy where it has the highest strength at $\beta = 90°$ (9579 MPa) and lowest at $\beta = 30°$ (10.28 MPa). The

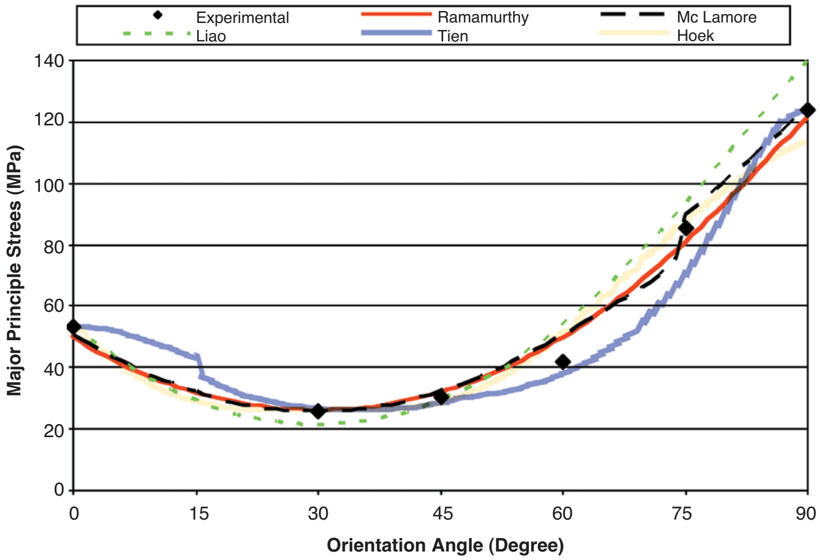

Figure 8—Comparison between predicted and experimental strength at σ_3 = 3 MPa

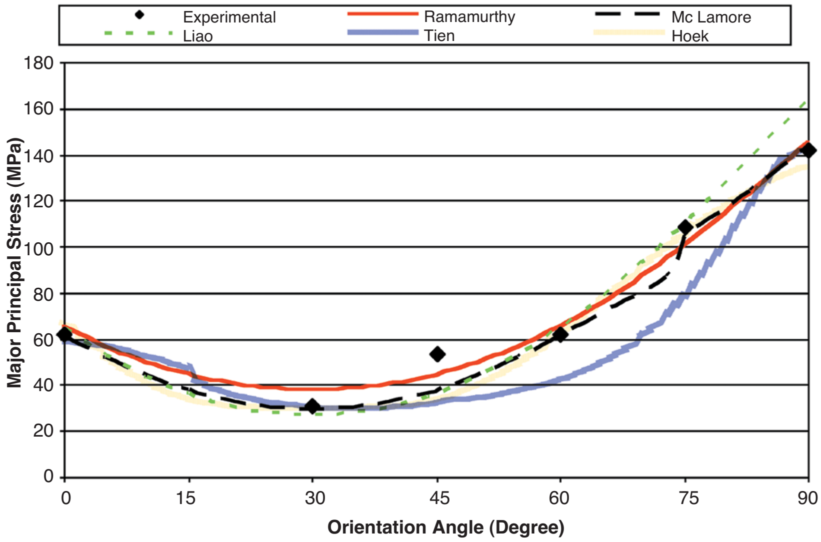

Figure 9—Comparison between predicted and experimental strength at σ_3 = 5 MPa

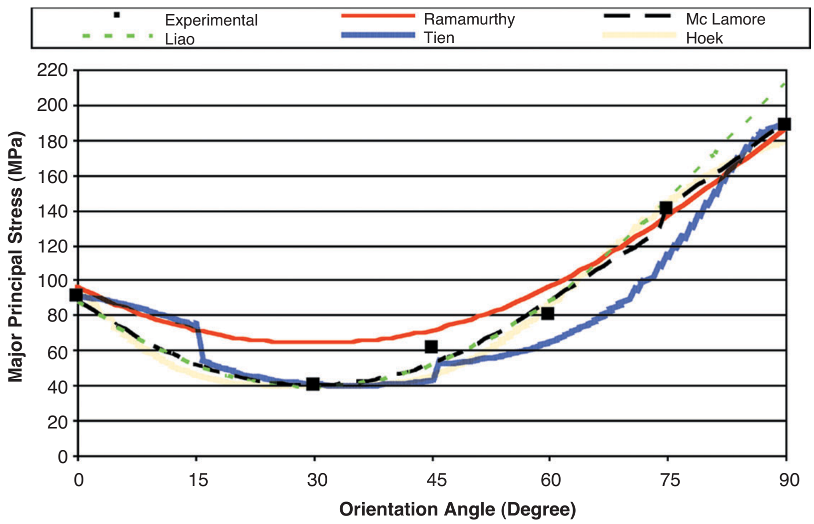

Figure 10—Comparison between predicted and experimental strength at σ_3 = 10 MPa

anisotropy ratio for this slate was found to be 9.32, which indicates that the slate can be classified as high foliation rock.

The triaxial test results also reveal that the slate has a U-shaped anisotropy and the highest and lowest strengths are at 90° and 30° respectively. The highest angle of internal friction (53°) occurs at $\beta = 90°$, which is the angle for intact rock and the lowest (19°) occurs at $\beta = 30°$, which is the internal angle of friction for the schistocity plane. The cohesion values for orientation angles below 60° are about 7 MPa and as the orientation angle increases, the cohesion increases too. The study show that for Hoek and Brown m and s constants, the m value has a U-shaped anisotropy, whereas the s value for orientation angles below 60° is constant and from then on as the orientation angle increases, the s value increases too.

In order to indicate the most suitable criterion for anisotropic rocks in uniaxial compression the Leo and Huong and Ramamurthy criteria were studied using 3 test results at $\beta = 0$, 30 and 90 degrees. The study shows that both criteria have good agreements with the test results; however, the Liao and Huong criterion predicts the strength more precisely. In triaxial compression the Hoek and Brown, Liao and Huong, Tien and Kuo, Mc Lamore and Ramamurthy criteria were studied. The results show that all criteria had good agreements with the test results; however the Hoek and Brown and Mc Lamore criteria predicts the strength more correctly. It should be noted that for Ramamurthy criterion only need to do three uniaxial compression tests in 0, 30 and 90° degrees and one triaxial test in 90° at two confining pressures. Therefore, this criterion can be the most suitable for investigating the behaviour of anisotropic rocks in triaxial compression.

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