Shahrood University of Technology
Iranian Society of Mining Engineering (IRSME)

Journal of Mining and Environment (JME)

journal homepage: www.jme.shahroodut.ac.ir

Vol. 11, No. 3, 2020, 711-720.
DOI: 10.22044/jme.2020.9220.1813

On Applicability of Some Indirect Tests for Estimation of Tensile Strength of Anisotropic Rocks

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Received 23 December 2019; received in revised form 11 February 2020; accepted 12 February 2020

Keywords

Tensile strength

Anisotropy

Schistose

Direction of foliation

Abstract

The tensile strength of rocks plays a noteworthy role in their failure mechanism, and its determination can be beneficial in optimizing the design of the rock structures. Schistose rocks due to their inherent anisotropy in different foliation directions show a diverse strength at each direction. The purpose of this work was to compare and assess the tensile strength of phyllite, which was obtained in direct and indirect tensile tests in different foliation directions. To this end, several phyllite specimens with different foliation angles (0º, 30º, 45º, 60º, and 90º) related to the loading axis (β) were prepared. Finally, the direct tensile test, diametrical and axial point load tests, Brazilian test, and Schmidt hammer test were conducted on 188 samples. The results of the experimental tests revealed that the maximum and minimum tensile strengths in direct tensile testing tension were directly related to the angles of 0º and 90º. Also it was observed that the Brazilian tensile strength overestimated the tensile strength. Furthermore, an exponential correlation was introduced between the direct tensile strength and the Brazilian tensile strength.

1. Introduction

One of the essential mechanical parameters in the rock engineering is the tensile strength of rocks. Many mining issues such as the stability of mining roofs and galleries in drilling and blasting are controlled by this factor involving the failure of rock masses. However, there is no universal settlement within the scientific community to introduce the best applicable test among the available standard tensile strength tests for experimental determination. On the other hand, some researchers believe that the tensile strength should not be assessed as a material property since the previous experimental investigations in this matter are so dissimilar [1, 2].

Also the tensile strength of rocks has been considered to be zero in most projects, which is risky in some circumstances. For example, drillability of rock or blasting effects depends upon the actual measured rock tensile strength. The proficiency of the progression would be overestimated by assuming zero tensile strength in any numerical analysis. In addition, the safety factor of a mine roof is highly affected by the tensile strength [3].

It is well-documented that rocks are tougher to compression or shear loading than to tension loading. Also tension cracks often grow earlier in comparison with compression or shear cracks. Moreover, tensile cracks can be sensed in rocks instantly after drilling or blasting, in the outline of a borehole, and in the superior surface of a failed slope [4-7].

Since determination of the tensile strength in experimental approaches, especially the direct test, can be difficult, expensive, and time-consuming, it is commonly preferred to estimate it by the indirect methods such as using empirical equations and/or statistical methods [8]. At the same time, the interpretation results of the laboratory or field investigation of the tensile strength are sometimes problematic. Thus understanding the rock behavior under tension circumstances can be useful in the

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analysis of intact rocks or rock masses in different projects.

One of the mostly applied indirect methods is the Brazilian test, which is used to evaluate the tensile strength of isotropic rocks; however, this method is not appropriate for anisotropic rocks. Also the direct tensile test is recommended in the case of anisotropic rocks. Nevertheless, the direct method has hardly been employed since the bending stresses (or torsion moment) and the anomalous concentrated stresses are normally unpreventable [5].

The key focus of the current conducted investigation was to investigate the tensile strength of anisotropic rocks (phyllite) and compare the ability to use a variety of evaluation techniques of tensile strength such as the direct tensile test, diametral and axial point load tests, Brazilian test, and Schmidt hammer test.

2. Anisotropic rocks

The anisotropy is the most distinct inherent parameter of rocks dealing with the mineral foliation in metamorphic rocks, stratification in sedimentary rocks, and discontinuities in rock masses. The failure or split in the foliated metamorphic rocks (e.g. slate, phyllite, schist, and gneiss) is generally parallel to the foliation or cleavage planes rather than through the planes or at other orientations. Many rocks can be categorized by their anisotropic characteristics like the mechanical, thermal, seismic, and hydraulic properties varying with respect to the anisotropy direction; thus ignoring this behavior can produce disastrous consequences in different rock engineering projects [9]. For instance, the rock-cutting performance in mechanized tunneling is governed by rock anisotropy, and it affects drilling boreholes in petroleum and geothermal engineering. Furthermore, for regularly-fractured rock masses, once the equivalent continuum method is employed, the anisotropy of rocks must be taken into account due to the main deformations along the discontinuities [10].

For a better understanding of the rock behavior during tension loading, the correlation among the mechanical behavior and the microcrack-induced anisotropy, in particular, is demanded [11-14]. Since for the anisotropic rocks the mechanical behavior should be determined in diverse directions, a far more number of samples are required by comparison with the isotropic rocks. It is so challenging to achieve a great number of field samples with unchanging properties on account of high inconsistency of the natural rock due to their formation development, geological environment, weathering and mineral composition, texture, fracture, crystal orientation, and joint characteristics [15]. However, the experimental evidence on the behavior of these rock types when subjected to tensile stress is inadequate [16].

3. Experimental investigation

The experimental tests in this work were conducted on the phyllite specimens. The procedure included the direct tension test and the indirect tension tests including the Brazilian and point load test and the Schmidt hammer test. The samples were tested in a dry condition. The results obtained from the laboratory tests are presented in the following sections. At least, three samples were tested for each foliation angle β.

3.1. Specimen preparation

A total number of 188 phyllite specimens from the Sanandaj-Sirjan zone in the Kurdistan Province were prepared, as received in the laboratory trials. The cylindrical samples with 54 mm in diameter were arranged in accordance with ISRM Testing Commission, and they were stored in a dry condition at room temperature. In this work, the specimen preparation was based upon the different anisotropy angles of the samples with respect to the loading axis at $\beta = 0^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}$, and 90º. Also to perform the Schmidt hammer test, some cubic specimens with a dimension of 12 cm were prepared and tested. Also according to a petrographical study, the phyllite specimens were formed from 10% quartz, 18% muscovite, 10% chlorite, and background with 50% of calcite, and the others were clay minerals and plagioclase [17].

3.2. Direct tension test procedure

A series of direct tension tests were carried out on the phyllite specimens. The samples with NX size (54 mm in diameter) and L/D = 2.5-3 with five different inclinations (β = 0°, 30°, 45°, 60°, and 90°) of foliation planes with respect to the tensile loading direction were used in this method of experimental trials. In order to connect the cylindrical specimen to the direct tension test device, two pairs of straight steel plates with a slightly different geometry and epoxy resin were used. In order to achieve the ultimate strength of the glue, testing of the samples was taken at least 48 hours after gluing the sample. An experimental setup including a servo-electric testing machine with a data acquisition system alongside the specimen placement are shown in Figure 1.

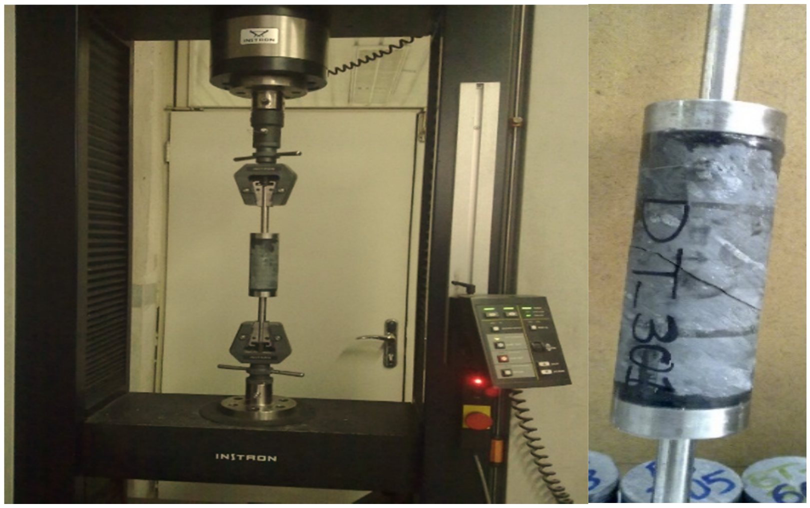


Figure 1. Servo-electric load frame and phyllite specimen.

3.3. Brazilian test procedure

The Brazilian test is a simple indirect testing technique used to achieve the tensile strength of brittle materials such as the concrete, rock, and rock-like materials. Recently, the influence of layer orientation on the failure mechanism through the Brazilian test has been studied [18-20].

Earlier, Fairhurst [21], Mellor and Hawkes [22], and Franklin [23] presented an equation to calculate the tensile strength of rocks. Then ISRM proposed the Brazilian test as a suggested method for determining the tensile strength of rock materials [24]. By assuming that the indirect tensile strength of the anisotropic rocks is equal to the maximum stress in the direction perpendicular to the axis of the loading at the center of disc, thus:

$$\sigma_t = -q_{xx}\frac{P}{\pi D t} \tag{1}$$

where q_{xx} is the stress concentration factor at the center of the disk, P is the maximum load, and D and t are the diameter and thickness of the rock specimen, respectively.

The dominant failure mode in this method can occur in four different types: a) centeral crack, b) slip in foliation, c) combining the central crack and slip in foliation, and d) non-centric crack. The dominant failure modes are shown in Figure 2. The centric cracks are located in the center of the samples and along the loading axis. The central share is the distances with 10% of the sample diameter length on both sides of the loading axis. Hence, the other centric cracks distancing more than this value are called the non-centric cracks [18].

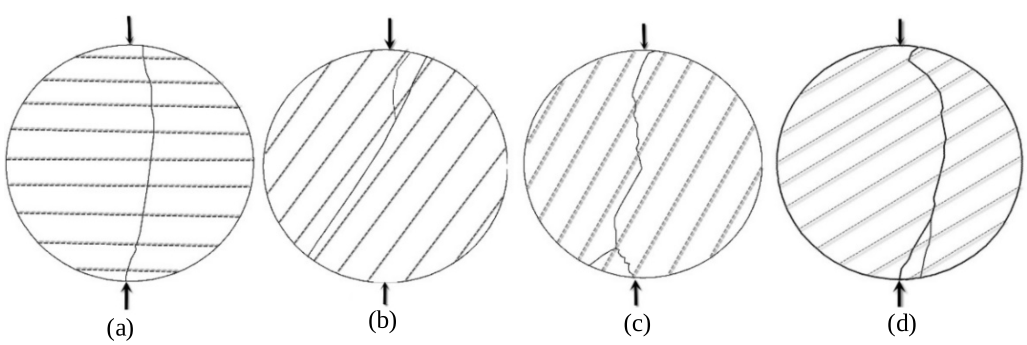


Figure 2. Four types of dominant failure in Brazilian method a) centeral crack, b) Slip in foliation, c) combining of the central crack and slip in foliation, and d) non-centric crack.

3.4. Point load test (PLT) procedure

Many geotechnical projects have been using the PLT method for over three decades [25]. Several researchers such as Chau and Wong [26] and Adrian & Muir [27] have reported their results based upon PLT. PLT involves the compressing of a rock sample between the conical steel plates until failure happens. The following equation has been suggested to determine the uncorrected point strength index $Is_{(50)}$ (MPa):

$$Is_{(50)} = \frac{P}{D_e^2} \tag{2}$$

where P is the failure load in MN and D_e is the equivalent core diameter (m).

3.5. Schmidt hammer test procedure

The development of the Schmidt hammer test was for the measurement of the strength of hardened concrete and rock [28-30]. The rebound height of the mass (R) is recorded on a linear scale, and it provides an indication of the strength of the material being tested [8]. All tests were accomplished with the hammer held vertically downwards and at right angles to the horizontal rock faces. All tests were done by L-type Schmidt hammer with a blow energy equal to 0.74 N/m. The recommended Schmidt hammer test procedures used in this study are as follow:

(1) ISRM: recording the 20 rebound values from single impacts divided by at least a plunger diameter, and average the upper 10 values [31];

(2) Hucka: the peak rebound value from 10 continuous impacts at a point and average the peaks of the three sets of tests conducted at three separate points [32];

(3) Poole and Farmer: the peak rebound value from five continuous impacts at a point and average the peaks of the three sets of tests conducted at three separate points [33];

(4) Fowell and Smith: the mean of the last five values from 10 continuous impacts at a point [34].

By different methods of the Schmidt hardness test, the optimum edge dimension of cubic sample was found to be 11 cm based upon the measurements performed. Also the *in situ* SRH value is equal to the SRH values achieved from the samples with the edge dimensions higher than 11 cm due to the *in situ* SRH measurements [35].

To employ the Schmidt hammer test, five cubic specimens with the dimension of 12 cm and different foliation angles of 0°, 30°, 45°, 60°, and 90° with respect to the direction of the impact were prepared. It should be noted that to prevent any movement of the specimens during the test, the specimens were fixed in the special clamps.

4. Results and discussion

4.1. Direct tension test

The results obtained from the direct tension method of the phyllite specimens in different foliation directions can be seen in Figure 3. In this method, the tensile strength is defined as the ultimate load divided by the original cross-sectional area of the test specimen. The strength change was due to varying the strength in different foliation directions.

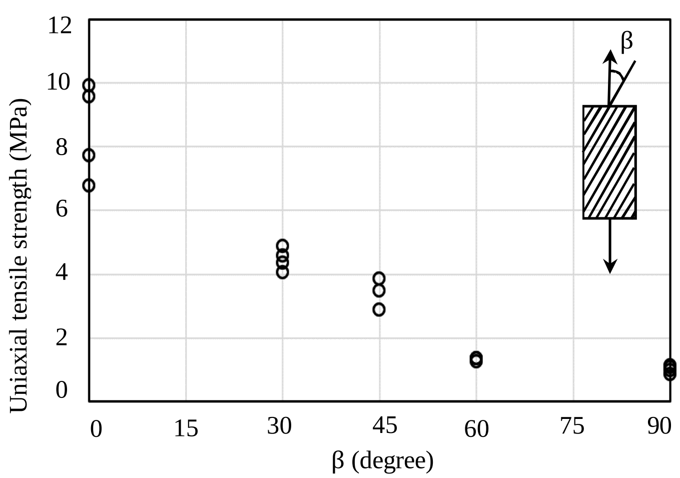


Figure 3. Tensile strength of phyllite specimens by direct tension test.

It was shown that the direct tensile strength decreases with increase in the foliation angle (β). It is worth mentioning that the maximum and minimum values of standard deviation of tensile strength are equal to 1.3 MPa and 0.05 MPa, which are related to the angles 0° and 60°, respectively. Moreover, some typical failed specimens of phyllite in direct tensile tests are shown in Figure 4.

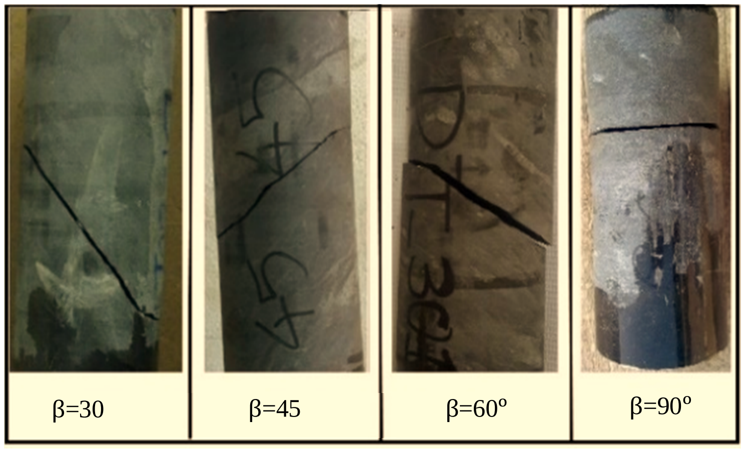


Figure 4. Some typical failed specimens of phyllite in direct tensile tests.

The uniaxial tensile strength test on rock materials is seldom carried out due to the practical problems of applying tensile forces to a cylindrical rock specimen; therefore, several indirect methods were developed for assessing the tensile strength [36].

4.2. Brazilian test

The Brazilian disc test was done on the specimens with NX diameter and L/D = 0.5. Figure 5 shows the Brazilian tensile strength values for samples with different foliation angles. Furthermore, the observed failure patterns for the Brazilian tests for different values of the foliation angle (β) of phyllite is shown in Figure 6. The test results show that the maximum and minimum strengths of the samples take place at angles of 90° and 30° equal to 9.56 MPa and 3.76 MPa, respectively. Also the minimum and maximum values for the standard deviation are related to the angles of 30° and 90°, and the amounts of these quantities are equal to 1.10 MPa and 2.82 MPa.

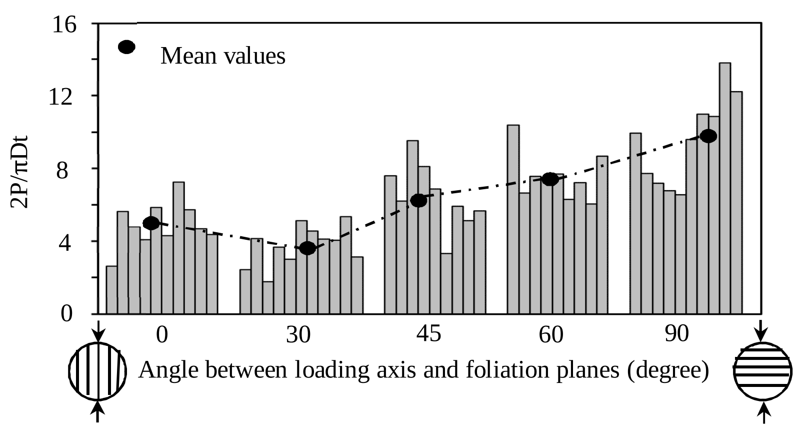


Figure 5. Variation in Brazilian tensile strength at different foliation angles (β).

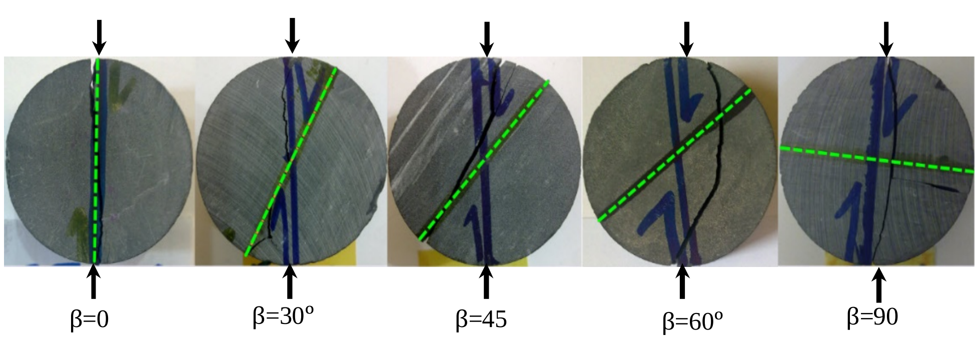


Figure 6. Observed failure patterns of Brazilian tests for different values of the foliation angle (β).

Moreover, Figure 7 shows the frequency graphs of the samples through four different failure modes at the different angles of 0°, 30°, 45°, 60°, and 90°. It can be concluded that at a low angle of β, especially when the loading axis is parallel to the foliation direction, the slip in foliation is a dominant failure mode. Firstly, by increasing β, combining the centric crack and slip in foliation occurs, and then the non-centric cracks can be sensed. Finally, the centric crack and slip in foliation failure modes decrease with increase in β.

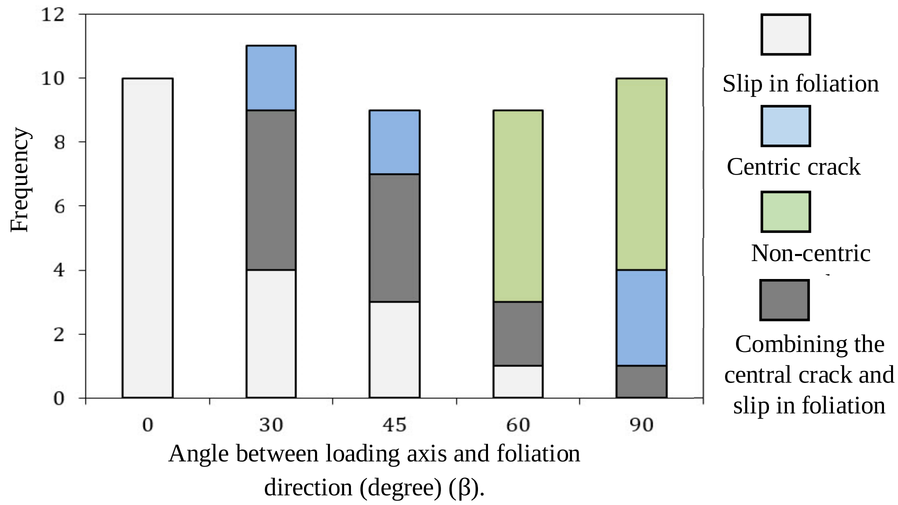


Figure 7. Frequency graphs of samples in four different failure modes at different foliation angles.

4.3. Correlation between direct tension test and Brazilian test

The average of direct tensile strength results divided by the average of Brazilian tensile strength results for the corresponding foliation angles to find a reasonable relationship between these two methods. This ratio, according to the cos2β for five achieved data, is plotted in Figure 8. It can be seen that there is a good correlation between the data for the horizontal and vertical axes. This correlation is as exponential function with a decision factor (R^2) equal to 0.9763 (Eq. 3).

$$q_{xx} = \frac{\sigma_t}{P/\pi D t} = 0.457\, e^{1.5 \cos 2\beta} \tag{3}$$

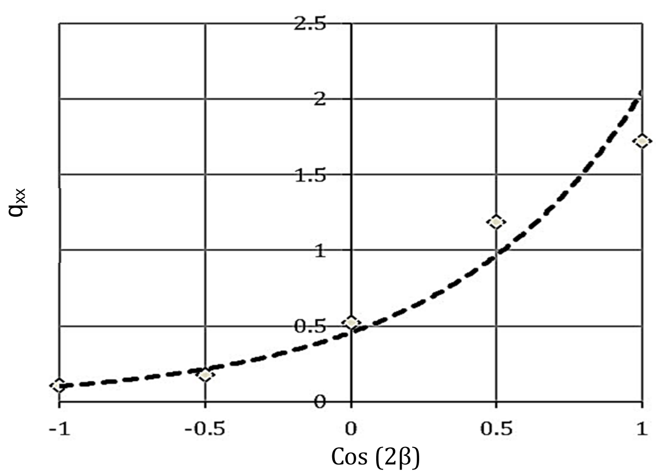


Figure 8. Correlation between stress concentration factor and Cos(2β).

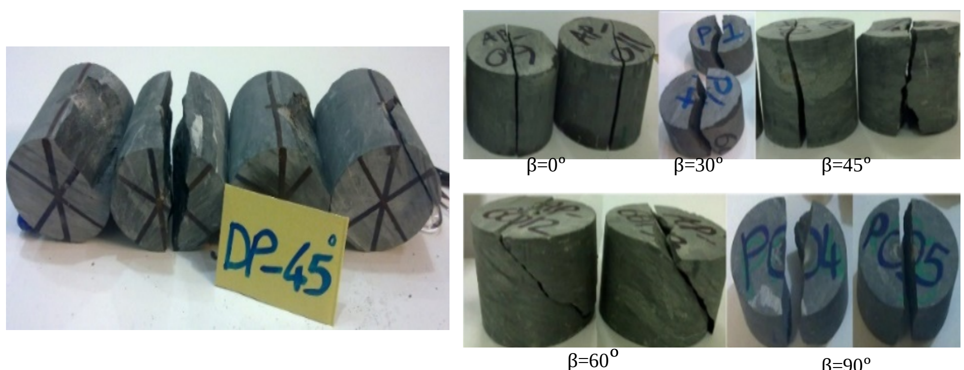
4.4. Point load test

In this work, two series of point loading tests on the phyllite samples were performed. The two types of tests are the axial point load test and the diametral point load test. The point load strength index (PLSI) has been correlated empirically with both the compressive and tensile strengths of rocks. Moreover, the point load test can be applied to cylindrical specimens either along the axis or the diameter; however, the diametral PLT is preferred to determine the rock tensile strength [37-39].

At first, the diametral point load test with L/D = 1 was done on the samples to evaluate the point load strength index in different directions but only the specimens in two direction of testing (0° and 90°) provide a valid failure mode. Then other specimens with L/D = 0.5-1 were prepared and tested through the axial point load test. The results of the diametral and axial point load tests for different directions of foliation can be seen in Table 1. Also Figure 9 shows some typical failed specimens of phyllite in both the axial and diametral loading stages.

Table 1. Results of diametral and axial point load tests.

β (degree)	Axial point load (MPa)				Diametral point load (MPa)			
	Min	Max	Mean	St.dev	Min	Max	Mean	St.dev
0	1.75	3.18	2.21	0.391	0.895	3.01	2.08	0.854
30	1.98	4.35	3.04	0.488				
45	2.56	6.66	4.99	1.159				
60	3.45	7.49	5.10	1.166				
90	4.03	9.88	6.51	1.396	6.39	7.23	6.71	0.370



(a) (b)

Figure 9. Some typical failed specimens (a) diametral point load test (b) axial point load test.

By increasing the foliation angle, the point load index shows an increasing trend. The following equation can be used to determine the anisotropy ratio:

$$I_{a(50)} = \frac{I_s(50)_{90^{\circ}}}{I_s(50)_{0^{\circ}}} \quad (4)$$

In both the axial and diametral point load tests, the ratios are equal to 3.23 and 2.95, respectively. According to the classification of schistose rocks, the nature of this rock is described as “strongly foliated, highly anisotropic” [40].

4.5. Schmidt hammer test

The results normalized with respect to the horizontal surface using the chart provided by Aydin and Basu [41] for this method based on the above-mentioned discussion in four different ways are summarized in Table 2. It can be seen that the maximum and the minimum values for all methods happen at the foliation angles of 0° and 60° associated with the axis of the impact load, respectively.

Table 2. Statistical results of SRH values according to four different test procedures.

β (degree)	ISRM				Hucka				Poole & Farmer				Fowell & Smith			
	Min	Max	Mean	St.dev	Min	Max	Mean	St.dev	Min	Max	Mean	St.dev	Min	Max	Mean	St.dev
0	51.5	57	54.7	1.9	55	61	57.7	3.06	55	60	56.7	2.89	55	61	57.8	2.28
30	52	57	54.3	1.7	50	55	52.3	2.52	49	55	52	3.00	51	53	51.8	0.84
45	45.1	49.1	46.8	1.3	51	53	52	1.00	49	53	50.7	2.08	47	51	49.4	1.82
60	44	47	45.7	1.2	44	50	47	3.00	44	50	47	3.00	45	47	46	0.71
90	46	50	47.7	1.4	47	54	51	3.61	45.5	54	50.5	4.44	50	52	51.2	0.75

The anisotropy ratio is the ratio of the maximum to minimum tensile strengths, and for the direct tension test is equal to 8.42. Moreover, the results of the anisotropy ratio for four different methods are shown in Table 3. It can be seen from the anisotropy ratio of the Brazilian test that the axial and diametral point load tests are close in value. Also the anisotropy ratio for different methods of the Schmidt hammer test is almost equal to 1.2. These results show a great deference with the results of the direct tensile test, so it is worth mentioning that using the Schmidt hammer test to estimate the tensile strength of anisotropic rocks may not be satisfactory.

Table 3. The obtained values of anisotropy ratio for four different methods.

Methods	Direct tension tests	Brazilian tests	Point Load tests		Schmidt hammer tests			
			Axial	Diametral	ISRM	Hucka	Poole & Farmer	Fowell & Smith
Anisotropic ratio	8.42	2.54	2.95	3.23	1.20	1.23	1.21	1.26

5. Conclusions

In general, one of the determinant factors of rock behavior is the anisotropy. Rock anisotropy is acted with more intensity in a tensile condition. Indeed, to understand the properties of a rock anisotropy, the tensile testing is more suitable. In the present work, an experimental investigation was carried out to evaluate the tensile strength of anisotropic rocks based upon the diverse test methods (direct tensile test, diametral and axial point load tests, Brazilian test, and Schmidt hammer test) through the different foliation angles of 0°, 30°, 45°, 60°, and 90°, and an exponential relationship between the direct tensile strength and the Brazilian test was revealed. Also in the Brazilian test, the maximum and minimum values for the tensile strength were equal to 13.80 MPa and 1.76 MPa, respectively. However, the maximum and minimum values of tensile strength in this test method occurred in the angles of 30° and 90°, respectively. Moreover, due to the anisotropic ratio of different test methods, the Brazilian test overestimated the tensile strength of anisotropic rocks.

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کاربرد روش‌های غیر مستقیم در تخمین مقاومت کششی سنگ‌های آنیزوتروپ

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ارسال 2019/12/23، پذیرش 2020/02/12

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چکیده:

مقاومت کششی سنگ‌ها به عنوان یکی از مهمترین پارامترهای ژئومکانیکی سنگ‌ها نقشی کلیدی در طراحی سازه‌های سنگی دارد. سنگ‌های آنیزوتروپ به واسطۀ ساختارهای ضعفی که ناشی از سطوح شیستوزیته یا لامیناسیون آنها می باشد مقاومت متفاوتی را در راستاهای مختلف بارگذاری خواهند داشت. از طرف دیگر، تعیین مقاومت کششی سنگ‌ها با استفاده از آزمایش کشش مستقیم، با چالش‌هایی نظیر مشکل بودن انجام آزمایش و هزینه بر بودن آن روبرو است. بنابراین همواره تلاش شده است تا از روش‌های غیر مستقیم برای تخمین مقاومت کششی سنگ‌ها استفاده شود. آزمایش‌هایی نظیر آزمایش برزیلی، بار نقطه‌ای و چکش اشمیت از جمله این آزمایش‌ها هستند که برای تخمین مقاومت کششی سنگ‌ها از آن استفاده می‌شود. علی رغم استفاده موفقیت آمیز از روش‌های غیرمستقیم برای تخمین مقاومت کششی سنگ‌های ایزوتروپ، استفاده از این آزمایش‌ها برای تخمین مقاومت کششی سنگ‌های آنیزوتروپ همواره با چالشی جدی همراه بوده است. در این مطالعه آزمایش‌های برزیلی، چکش اشمیت و بار نقطه‌ای بر روی نمونه‌هایی از جنس فیلیت با زوایای مختلف شیستوزیته، انجام شده است و در ادامه مقادیر مقاومت کششی بدست آمده از این آزمایش‌ها، با مقادیر مقاومت کششی که از آزمایش‌های کشش مستقیم بدست می‌آید مقایسه شده است. نتایج آزمایش‌های انجام شده نشان می‌دهد که آزمایش برزیلی نسبت به آزمایش چکش اشمیت و بارنقطه ای، برای تخمین مقاومت کششی سنگ‌های آنیزوتروپ مناسب‌تر است. همچنین آزمایش برزیلی، مقادیر بالاتری از مقاومت کششی سنگ‌ها را در مقایسه با آزمایش کشش مستقیم ارائه می‌دهد. این تخمین بالاتر مقادیر مقاومت کششی، در همه زوایای آنیزوتروپی با نسبت‌های متفاوت مشاهده می شود. در ادامه رابطه‌ای نمایی برای تخمین مناسب مقاومت کششی سنگ‌های آنیزوتروپ در آزمایش برزیلی، ارائه شده است تا مقاومت کششی سنگ ها را با دقت بالاتری در زوایای مختلف آنیزوتروپی محاسبه نماید.

کلمات کلیدی: سنگ‌های آنیزوتروپ، مقاومت کششی، آزمایش برزیلی، چکش اشمیت، آزمایش بار نقطه‌ای.
