Direct Tension Tests of Intact Rocks Using Compression-to-Tension Load Converter

Kittitep Fuenkajorn and Sippakorn Klanphumeesri

Geomechanics Research Unit, Institute of Engineering, Suranaree University of Technology,

Muang District, Nakhon Ratchasima, Thailand 30000.

Phone (66-44) 224-758, Fax (66-44) 224-448

E-Mail: kittitep@sut.ac.th

Abstract

Direct tensile strength and stiffness are determined from dog-bone shaped specimens of intact sandstone, limestone and marble. A compression-to-tension load converter is developed to allow a of the elastic modulus and Poisson's ratio under tensile and compressive loadings on the same specimen. A series of finite difference analyses are performed to obtain the most suitable specimen configurations. For all rock types the direct tensile strengths are clearly lower than the Brazilian and ring tensile strengths. The elastic moduli and Poisson's ratios under uniaxial tensile stress are lower than those under uniaxial compressive stress, probably because the effort required to dilate the pore spaces and fissures in the rocks under tensile loading is lower than that to contract them under compressive loading. As a result these rocks tend to be stiffer under compression than under tension.

1. Introduction

Tensile strength of rock is an important parameter used in the design and stability analysis of underground structures. Rock tensile strength dictates the maximum roof span of underground openings, the maximum internal pressure of unlined storage caverns, the stability of boreholes under highly anisotropic stress states, and the borehole pressures for hydraulic fracturing. The direct tension test [1] may not be applicable to high strength rocks due to the limited performance of the cementing adhesive between the loading platens and sample end surfaces. The Brazilian tension test [2] has been widely used to obtain rock tensile strengths due to the simplicity of sample preparation and testing. It however can not provide the elastic parameters under pure tension. To overcome the strength limitation of the direct tension method Plinninger et al. [3] propose the modified tension test to determine the rock strength under unidirectional condition. Even though their test method is simple, the results do not truly represent the direct tensile strength, and a measurement of the tensile elastic properties from the proposed specimen configurations is not possible.

It has been recognized that the rock elastic modulus under tension may differ from that under compression. The mechanisms governing such discrepancy have not been adequately described. Jianhong et al. [4] determine the tensile elastic moduli of four rock types from the Brazilian tests by measuring the total deformation of the loaded diameter and combining with complex analytical solutions. They conclude that the tensile elastic modulus is lower than the compressive elastic modulus. Liao et al. [5] however conclude from their experimental results that the tensile elastic modulus of argillite is comparable to that under compression. Without the closure of the rock pore spaces the elastic modulus under tension would exceed that under compression.

The objective of this paper is to determine the direct tensile strength and stiffness of intact rock specimens. The effort involves development of a compression-to-tension load

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converter, finite difference analysis, and measurements of the rock tensile strengths and stiffness. The tensile strengths and elastic parameters obtained from different test methods are compared to improve our understanding of the rock failure and deformation under tension.

2. Compression-to Tension Load Converter

A compression-to-tension load converter (CTC) was developed to determine the strengths and elastic parameters of dog-bone shaped specimen under uniaxial tension and compression. Its mechanism allows alternating between the applications of tensile load and compressive load on the same specimen while placing in a conventional compression machine. The deformation characteristics of the same specimen under both tension and compression can be measured, hence eliminating any intrinsic variability among the tested specimens. Figure 1 shows the CTC device arranged for the tensile and compressive loading. Under direct tension testing the end plates, which are separated from the specimen, transfer the compressive load through the steel columns to the bearing plate at the opposite ends. This induces a tensile force in the specimen mid-section. For compression testing the four loading blocks are rotated 90 degrees, slipping through the pre-cut slots, and hence the bearing plates are free of load. This allows the end plates to press on the specimen ends, and subsequently the mid-section will subject to the applied compressive load.

3. Rock Samples

Phu Phan (PP) sandstone, Saraburi (SB) marble and SB limestone were selected for this study. These fine-grained rocks have highly uniform texture. They were cut and machined to obtain dog-bone shaped cylinders with a total length of 24 cm. The diameter at both ends is 10 cm with 5 cm long. The mid-section diameter increases from 3 cm at the center to 6 cm at both ends (Figure 2).

The specimen size and shape above are the end results of several trials of finite difference simulations using FLAC [6]. The axis symmetry analyses were made under a variety of specimen configurations, assuming that the rock was

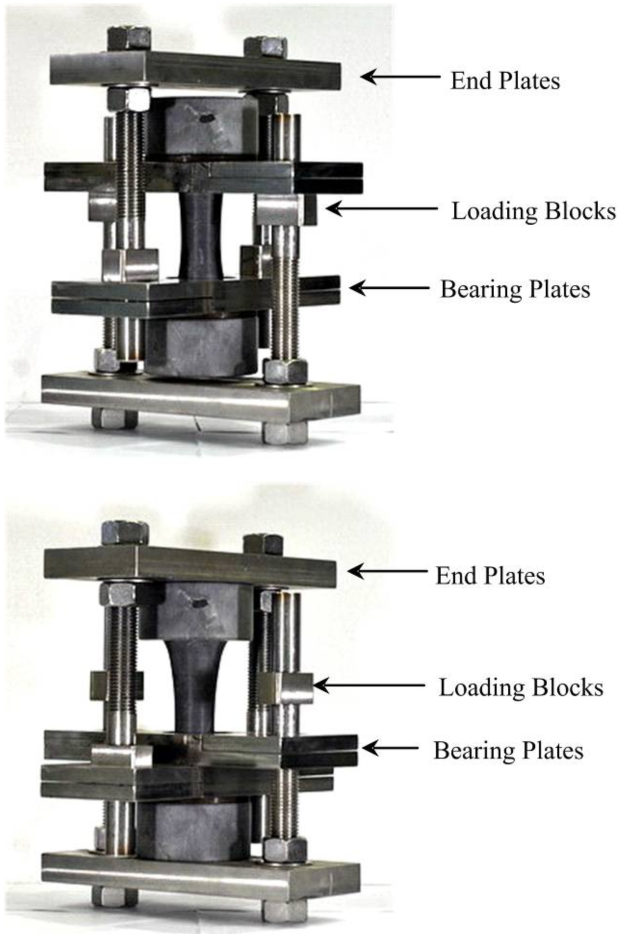

Figure 1 Compression-to-tension load converter arranged for tensile loading (top) and compressive loading (bottom).

Figure 2 SB limestone (left), SB marble (middle) and PP sandstone (right) specimens prepared for direct tensile testing.

linearly elastic and isotropic. The primary objective is to ensure that the uniaxial tensile stress is uniformly distributed across the mid-length diameter, and that a tensile failure occurs before compressive shear failure is induced near the specimen ends. The stress distributions across the specimen diameters obtained from FLAC simulations for the proposed specimen configurations are plotted for the compressive and tensile loading conditions in Figure 3. Under tensile loading, the axial stress normalized by the applied stress (σ_{ax}/P_t) at the mid-length diameter (A-A’) is virtually uniform – the variation is less than 1.4%. The normalized axial compressive stress (σ_{ax}/P_c) at the mid-length is perfectly uniform. Away from the mid-length the induced stresses become lower and non-uniform because the specimen diameter is larger toward the ends and closer to the load bearing areas where high shear stresses are concentrated (sections B-B’ and C-C’ in Figure 3). The shear stresses along A-A’ section are zero for all cases.

4. Tensile Strength Test

The CTC device was placed in a compression load frame to apply uniaxial tensile stress at the mid-section of the specimen. Five specimens from each rock type were loaded at a constant rate of 1 MPa/s until tensile failure occurred. A splitting tensile failure was induced in the mid-section of all specimens (Figure 4). The tensile strengths are determined by dividing the applied load by the cross-sectional area where the actual tensile crack was induced. The strength results are summarized in Table 1.

Brazilian and ring tensile strength tests were performed on the three rock types. For the Brazilian testing the sample preparation, test procedure and strength calculation follow the ASTM D 3967 [1] standard practice. The specimen diameter is 10 cm and the length 5 cm. The ring test specimens are 5 cm long with nominal outer and inner diameters of 10 cm and 3 cm. The strength calculation follows the solutions given by Jaeger and Cook [7]. Table 1 compares the results from the two methods. Figure 5 shows the post-test specimens from Brazilian and ring tensile strength testing.

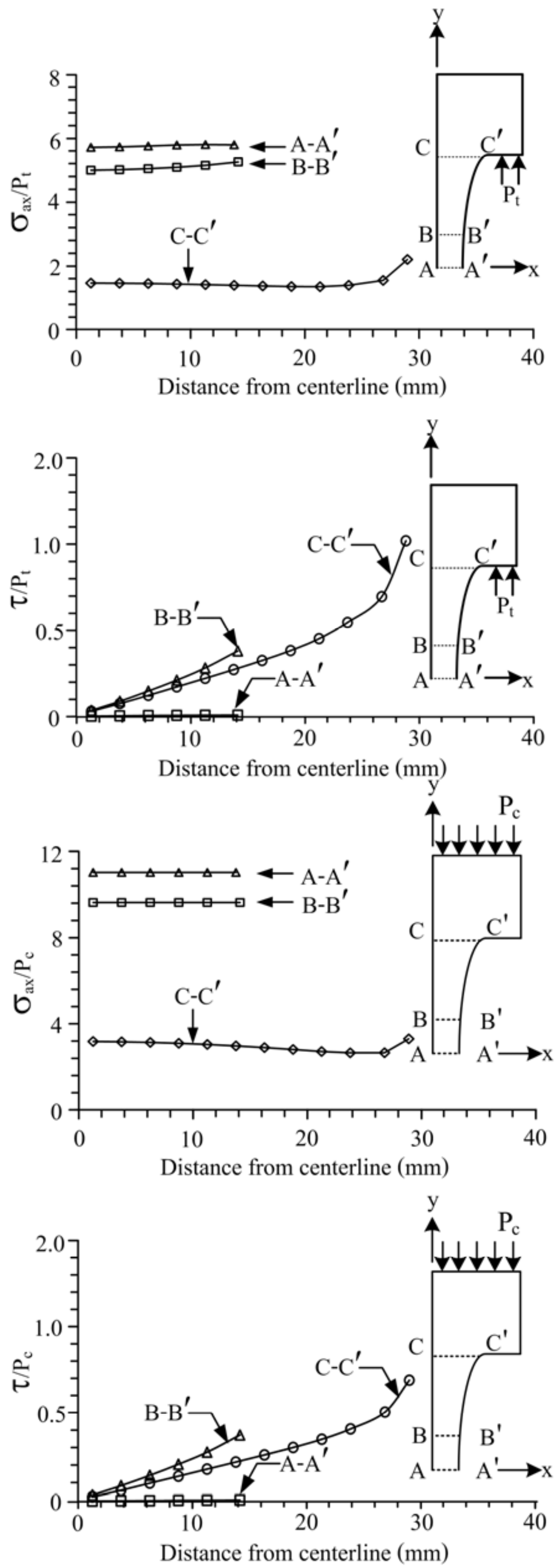

Figure 3 Axial and shear stresses across specimen diameters for tensile loading (top two) and compressive loading (bottom two).

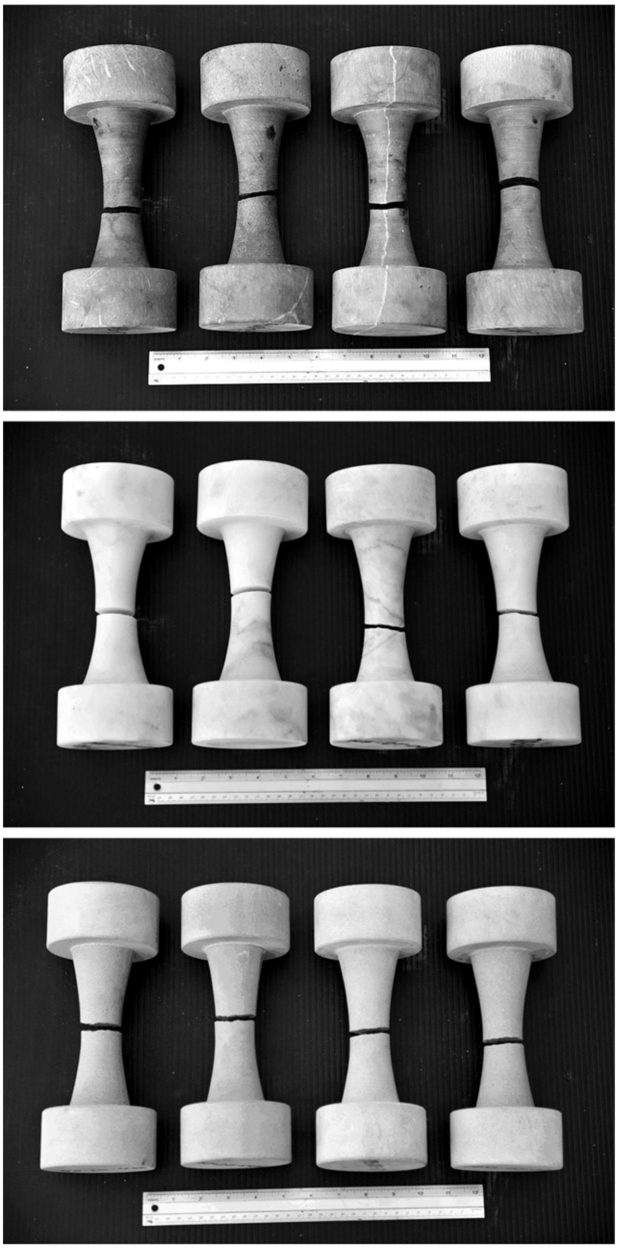

Figure 4 Post-test specimens of SB limestone (top), SB marble (middle) and PP sandstone (bottom).

Table 1 Summary of direct and indirect tensile strengths.

Rock Type	Density (g/cc)	Direct tensile strength (MPa)	Brazilian tensile strength (MPa)	Ring tensile strength (MPa)
PP sandstone	2.36±0.12	6.49±0.22	10.68±0.70	16.10±3.00
SB marble	2.65±0.08	6.33±0.62	8.02±0.25	20.59±1.24
SB limestone	2.81±0.05	9.31±0.65	10.90±0.19	23.18±1.70

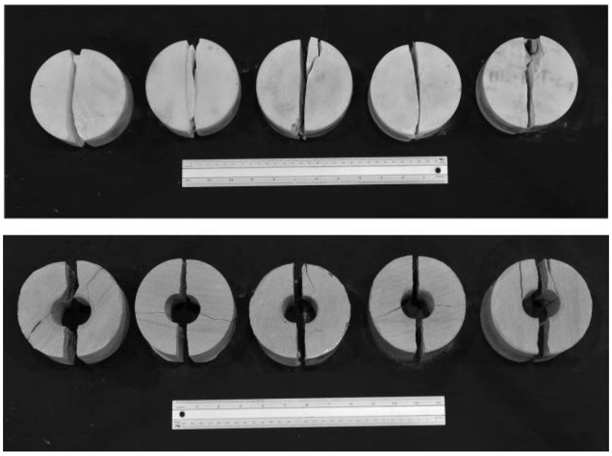

Figure 5 Some post-test specimens from Brazilian (top) and ring (bottom) tensile strength testing.

The ring tension test yields the highest strength values due to the high stress gradient along the incipient crack plane (e.g., [7]). The direct tensile strength is clearly lower than the Brazilian tensile strength, which agrees with the experimental results obtained by Plinninger et al. [3], but disagrees with those of Liao et al. [5]. It is interesting to note that the porous PP sandstone shows the largest difference between the Brazilian and direct tensile strengths (about 40%) compared to that of the denser SB marble and limestone (about 15%-21%). The difference of the tensile strengths from the two methods may therefore be partly governed by the amount and distribution of pore spaces and fissures in the rocks.

5. Elastic Parameters under Tension

To determine the elastic parameters under uniaxial tensile stresses three additional dog-bone shaped specimens for each rock type were mounted with strain gages at the mid-section and loaded up to 4 MPa. The specimen was subjected to one cycle of loading and unloading under uniaxial tension and compression. Figures 6 through 8 shows the axial stresses (σ_{ax}) as a function of axial and lateral strains (ε_{ax}, ε_{lat}) for some specimens. The elastic parameters are calculated from the tangent of the curves at the

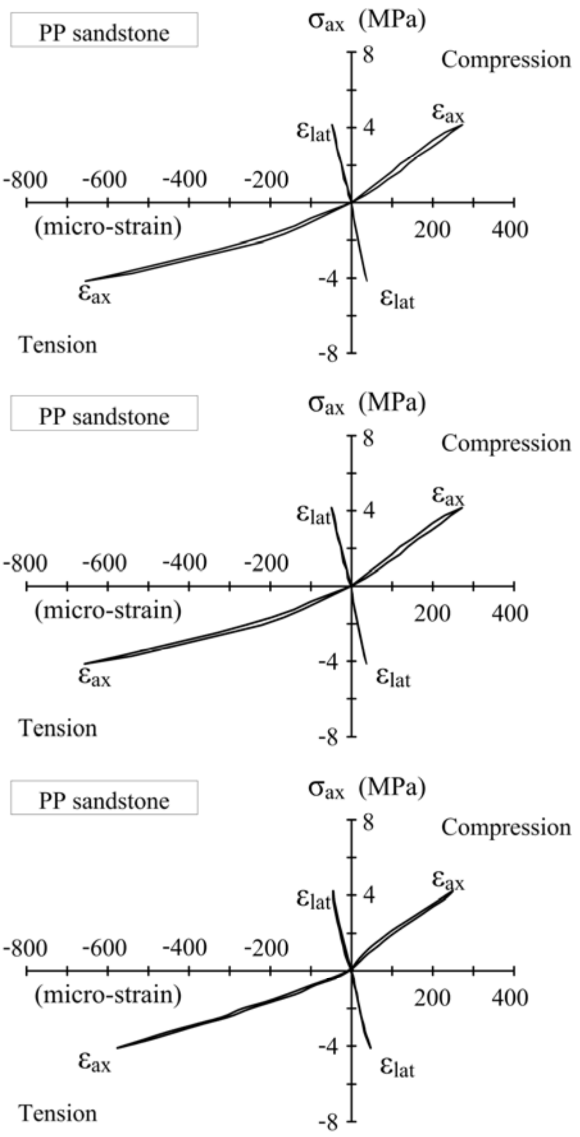

Figure 6 Axial stress (σ_{ax}) as a function of axial and lateral strains (ε_{ax}, ε_{lat}) for one cycle of compression and tension loading of PP sandstone specimens.

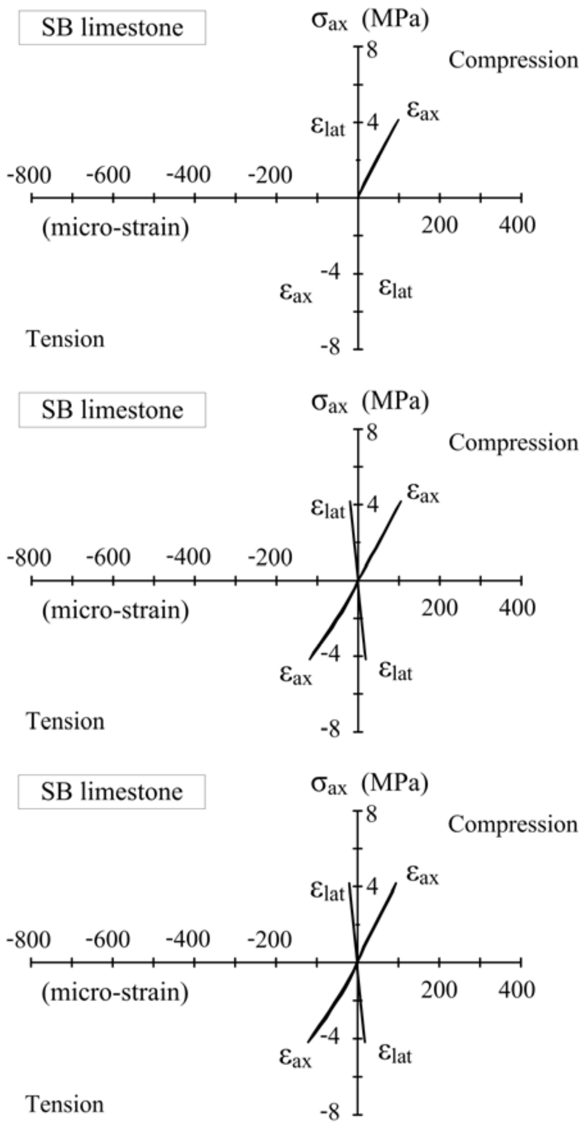

Figure 7 Axial stress (σ_{ax}) as a function of axial and lateral strains (ε_{ax}, ε_{lat}) for one cycle of compression and tension loading of SB limestone specimens.

maximum applied stress. For all rock types the tensile elastic modulus (E_t) is lower than the compressive elastic modulus (E_c) measured from the same specimen (Table 2). This agrees with the experimental results by Jianhong et al. [4]. The Poisson's ratios under uniaxial tension (ν_t) are slightly lower than those calculated from the uniaxial compression (ν_c), which agrees with the postulation by Gercek [8].

6. Discussions and Conclusions

The CTC device is designed specifically to obtain a direct comparison of the elastic parameters under uniaxial tensile and compressive loads from the same specimen, and to induce extension failure under a true uniaxial tensile stress. The proposed testing technique is not intended to replace the conventional method of elastic parameter measurements under uniaxial compression. The test diameter at the mid-section is

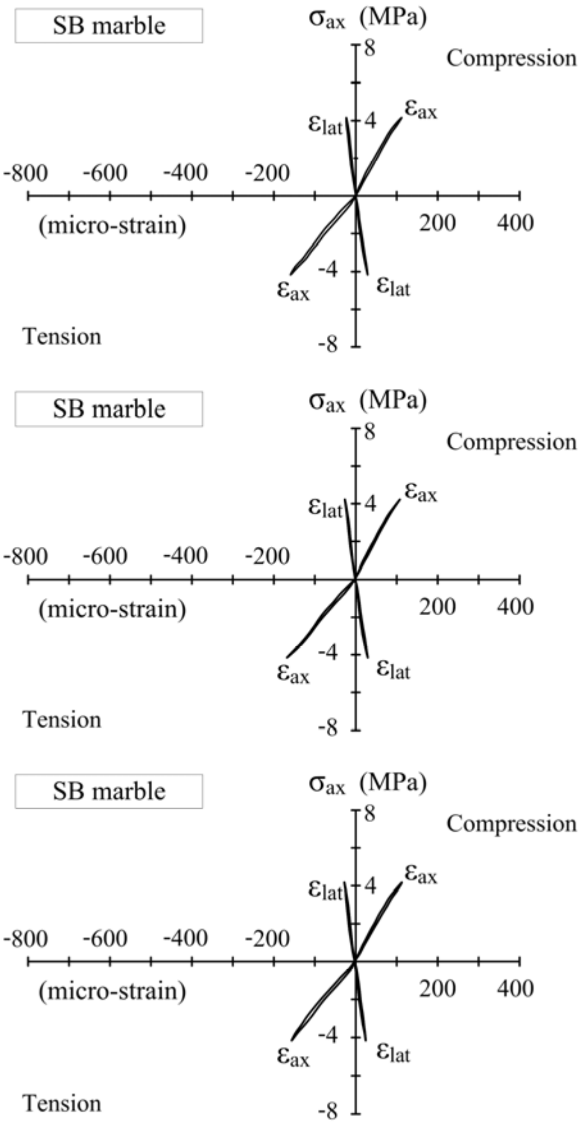

Figure 8 Axial stress (σ_{ax}) as a function of axial and lateral strains (ε_{ax}, ε_{lat}) for one cycle of compression and tension loading of SB marble specimens.

Table 2 Elastic parameters obtained from tensile and compressive loadings.

Rock Type	Elastic Modulus (GPa)		Poisson's Ratio	
	E_c	E_t	ν_c	ν_t
PP sandstone	16.23±1.95	6.73±0.35	0.17±0.01	0.05±0.005
SB marble	41.66±2.08	34.43±0.95	0.19±0.01	0.15±0.003
SB limestone	37.15±0.99	26.13±1.06	0.21±0.01	0.18±0.005

smaller than that recommended by the ASTM standard practices, which may raise an issue of size effect on the measured strengths. This nevertheless does not change the conclusions drawn from the test results above. If the size effect is present, the direct tension tests with a larger specimen diameter would yield even lower strength than the values reported here. To obtain the mid-section diameter of 54 mm or larger, the total specimen length will become impractical for preparation and testing.

The test results indicate that the direct tensile strengths of PP sandstone, SB limestone and SB marble are lower than the Brazilian tensile strengths. This probably holds true for other rocks with comparable physical properties. The rock elastic modulus and Poisson's ratio under tension are also significantly lower than those under compression. We agree with the postulations given by Gercek [8] that the discrepancies probably relate to the amount and distribution of the pore spaces and micro-fissures (inter-crystalline boundaries and cleavages), and the bond strength of cementing materials. As suggested by the test results here, the porous and relatively poor-bonding PP sandstone shows the largest difference between the tensile and compressive elastic moduli - E_t is about 40% of E_c. The tensile and compressive elastic moduli for the dense and well-bonding SB limestone and marble are less different (E_t = 70%-80% E_c). Under uniaxial tension the Poisson's ratio (ν_t) is lower not only because the axial tensile strain becomes larger, but also the lateral (transverse) compressive strain is smaller compared to those under uniaxial compression. The pore spaces in rock matrix probably dilate easier under tensile load than they do under compressive load. The findings suggest that for a conservative approach the rock uniaxial (direct) tensile strength and tensile elastic modulus should be recognized in the stability analysis of underground structures that are subject to tensile loads.

7. Acknowledgement

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