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Tensile strength of rocks: Comparison of different testing methods

Résistance à la traction des roches: Comparaison de différentes méthodes d'essai

J. Castro*, J. Justo, M.H. Olson, M. Miranda
Universidad de Cantabria, Santander, Spain

**castrogj@unican.es*

ABSTRACT: While direct tensile testing is widely acknowledged as the most accurate method of determining tensile strength, indirect methods are frequently employed, due to the problems and the precision required to obtain viable results with the direct method. Accurate values of tensile strength are very important, especially for design purposes. Thus, values obtained from the direct tensile test are beneficial and they should be compared to other experimental values measured with different methods. This study compares experimental results of standard methods of indirect tensile testing, such as the Brazilian (splitting tensile) test and three and four point bending flexural tests with the ones obtained from direct tensile testing performed following the ASTM standard. For the comparison, a highly isotropic and uniform rock, namely a Moleanos limestone, is used. Results show that bending tests produce higher values than those obtained using the Brazilian test, and in turn, the latter produces also slightly higher values than direct tensile testing.

RÉSUMÉ: L'essai de traction directe est généralement considéré comme la méthode la plus précise pour déterminer la résistance à la traction ; cependant, les méthodes indirectes sont souvent utilisées en raison de la difficulté et de la précision requises pour obtenir des résultats viables avec la méthode directe. Il est important d'obtenir des valeurs de résistance à la traction précises, en particulier pour la conception, c'est pourquoi les valeurs obtenues à partir de l'essai de traction directe sont utiles, pour pouvoir les utiliser et les comparer à d'autres valeurs expérimentales et à d'autres méthodes. Cette étude compare les résultats expérimentaux des méthodes standard d'essais de traction indirects, tels que l'essai brésilien (traction par fendage) et les essais de flexion à trois et quatre points, avec ceux obtenus à partir d'essais de traction directs réalisés conformément à la norme ASTM. Pour la comparaison, une roche hautement isotrope et uniforme, à savoir un calcaire du Moleanos, est utilisée. Les résultats montrent que les essais de flexion produisent des valeurs plus élevées que celles obtenues à l'aide de l'essai brésilien et, ces dernières produisent également des valeurs plus élevées que celles obtenues avec de l'essai de traction directe.

Keywords: Tensile strength, Brazilian test, direct tensile test, three-point bending test.

1 INTRODUCTION

Measuring the tensile strength of rocks is critical due to their sensitivity to tensile loading, which is a common cause of failure. However, accurately measuring this strength is challenging due to the low tensile strength of rocks and various factors that affect the stress state during testing. The direct tensile (DT) test (Figure 1) is the common method for many construction materials, such as steel, but it may not always be feasible or accurate enough for rocks.

The difficulties associated with conducting direct uniaxial tensile tests on rocks have resulted in the development of different variations of the test, such as using dog-bone specimens or indirect methods (Table 1). These indirect methods involve experimental configurations that create inhomogeneous stresses in the specimen. However, when interpreting the results from these indirect methods, the multi-axial stress state and the influence of other components of the stress tensor are usually not considered. Additionally, linear elastic behavior is typically assumed.

Table 1. Summary of tensile testing methods.

Name	***Reference***
Glued end caps	ISRM (1978); ASTM (2020)
Split grips	Hawkes and Mellor (1970)
Confined biaxial ext.	Brace (1964)
Comp.-tension convert	Gorski (1993)
Brazilian splitting test	ISRM (1978); ASTM (2008)
3-point bending test	Franklin and Dusseault (1989)
4-point bending test	Franklin and Dusseault (1989)
Sleeve fracturing test	Franklin and Dusseault (1989)
Modified tension test	Luong (1990)

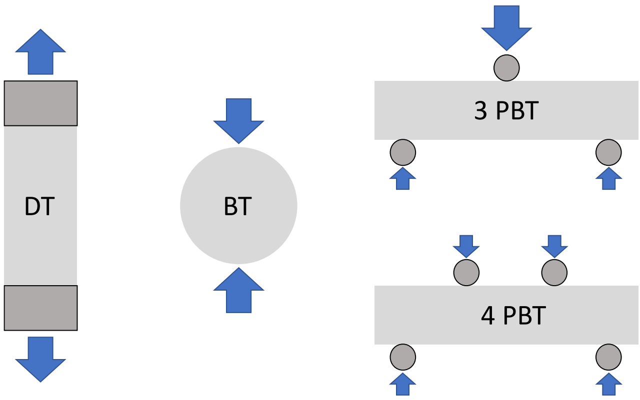

Figure 1. Summary of performed tests to measure Moleanos limestone tensile strength.

Among the indirect tensile tests, the bending of prismatic bars with circular or rectangular cross sections is widely used in mechanical and civil engineering to assess the tensile strength of various materials, such as ceramic materials, rocks, mortars... Three (3PT) and four (4PBT) points bending tests (Fig. 1) are adopted as a standard (e.g., ASTM C99: 2018, ASTM C880: 2018).

In rocks, the so-called Brazilian (splitting tensile) test (BT) (ASTM D3967: 2008) is commonly used due to the cylindrical shape of specimens. This test is preferred as it is relatively easy to prepare specimens, the testing method is straightforward, and the results obtained from the test exhibit low variability (Coviello et al., 2005). Detailed discussions on the Brazilian test have been presented by various authors (e.g., Colback, 1966), emphasizing its relevance in rock testing.

In recent years, with the development of high resistance glues that make easier using glued end caps, the direct tensile test is being revisited (e.g., Jensen, 2016; Zhang et. al., 2021; Pérez-Rey et al., 2023). In this way, the direct tensile test has recently been developed and implemented at the Geotechnical Engineering Laboratory of the University of Cantabria (Spain), following the ASTM standards with glued end caps (Castro et al., 2023).

Using the variety of tensile testing methods available (Figure 1), the different results obtained in a sample material, namely Moleanos limestone, are here compared and analysed, complementing existing comparisons between different testing methods to obtain the tensile strength (e.g., Coviello et al. 2005, Perras & Diederichs 2014).

2 LITERATURE REVIEW

Several authors have compared different methods to measure the tensile strength of rocks in the laboratory. For example, Coviello et al. (2005) compared tensile strength values measured with different tests, namely direct tensile test, Brazilian test, ring test, three and four-point bending tests and the Luong test (LT). They tested an artificial building stone (Gasbeton) and a natural calcarenite of the Gravina di Puglia geological formation. DT tests were perfomed using glued end steel caps and spherical joints in both ends. Good aligment was ensured and inclinometers were mounted on the lateral surface of the specimens. This is likely the reason to the fact that measured tensile strength using DT tests was higher than usual. Bending tests provided higher tensile strengths than those measured using the BT, and LT provided the lowest values.

On the other hand, Wang et al. (2020) performed tests on a granite from China and obtained that BT provided the higher tensile strength values in comparison to other methods, such as hydraulic fracturing hollow-cylinder, LT and DT tests.

Tensile strength obtained using bending tests relies on the linear elastic behaviour of the rock until failure. Thus, tensile strength is usually overestimated when using bending tests, unless a large thickness specimen is used (e.g., Biolzi et al., 2001).

For the DT test, some authors (e.g., Biolzi et al., 2001; Rabat et al., 2023) introduce a notch at the mid-section, but that could concentrate stresses and give overconservative tensile strength values.

As a brief summary, Table 2 compares the DT/BT ratio measured by different authors. More complete information and comparisons may be found for example in Perras and Diederichs (2014) or Rabat et al. (2023).

Table 2. Literature review of the relative tensile strength measured using direct tensile tests and Brazilian tests.

DT/BT ratio	***Rock***	***Reference***
0.98-1.07	Calcarenite	Coviello et al. (2005)
1.60	Gasbeton	Coviello et al. (2005)
0.84	Granites	Perras & Diederichs (2014)
0.69-0.93	Dataset	Perras & Diederichs (2014)
0.99-1.10	Schist	Ramana and Sarma (1987)
0.96-1.21	Granite	Ramana and Sarma (1987)
0.85	Quartz	Ramana and Sarma (1987)
0.71-0.84	Granite	Wang et al. (2020)

3 LABORATORY TESTING

3.1 Moleanos limestone

Moleanos limestone may be classified as an intrasparitic-pelsparitic limestone or grainstone. The most abundant components are pellets and intraclats, comprising 51% and 43% of the grains, respectively, with an additional 6 % of bioclasts. This limestone has been previously analyzed by the authors (e.g., Justo et al. 2017, 2021) and it is predominantly isotropic and relatively homogeneous from a microstructural point of view, which simplifies the analysis.

3.2 Indirect tensile tests

6 BT tests were performed (Table 2) on disc-shaped specimens with a diameter of 64 mm and a thickness of 32 mm (Figure 2). The tests were performed under displacement control at 2.5 mm/min following ASTM standards (ASTM D3967: 2008).

For the bending tests, parallelepiped 180x30x30 mm specimens were used. A repetitiveness of 3 was used for both 3 and 4 PBT (Table 3). It is worth noting that both specimen size and repetitiveness are low and larger specimens and more tests should be used for an improved accuracy. The support span at the base was 150 mm and the upper loading span for the 4PBT was 50 mm.

All the tested specimens failed as expected (i.e., along a vertical central plane).

Table 3. Summary of performed laboratory tests.

Type	***Number***	***Result, σ_t (MPa)***
BT	6	7.8, 7.7, 7.1, 7.0, 6.8, 4.8
3PBT	3	10.8, 9.5, 9.2
4PBT	3	11.0, 10.1, 9.1
DT	15	7.9, 7.7, 7.6, 7.5, 7.3, 7.3, 6.4, 6.3, 6.3, 5.5, 5.3, 5.2, 5.2, 5.1, 4.4

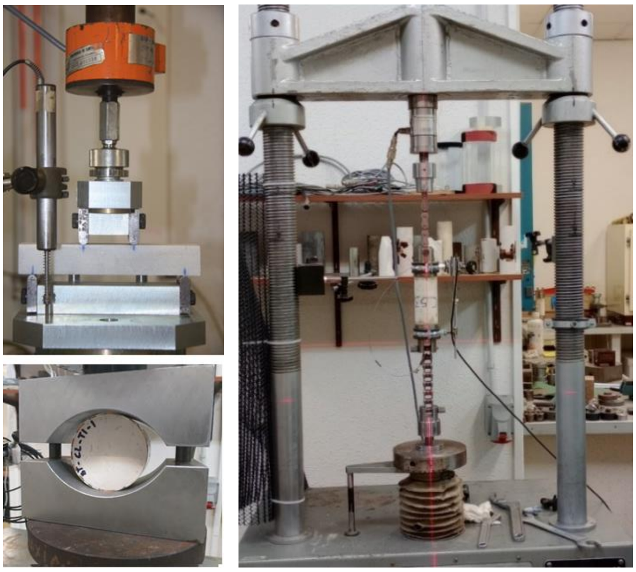

Figure 2. Test set-up of the different tests.

3.3 Direct tensile tests

DT tests were implemented at the Geotechnical Engineering Laboratory of the Univerisity of Cantabria mainly following the ASTM D2936: 2020. Samples of 50 mm diameter with a length diameter ratio of 2.5 were employed. They were glued to the metallic caps of 300 mm thickness and same diameter. Efforts were made to achieve a good alignment and failure of DT samples was reached in any area of the central part and was approximately horizontal. Detailed description of the DT tests may be found in Castro et al. (2023).

4 COMPARISON OF RESULTS

The interpreted tensile strength, σ_t, measured in each test is presented in Table 3 and plotted in Figure 3. The dispersity of the results for the DT is slightly higher than that of the BT (standard deviation of 1.15 vs 1.08 MPa).

The tensile strength predicted by the DT is the lowest. This is attributed to the fact that any misalignment introduces bending moments that reduce the theoretically calculated value. Nevertheless, the difference between the DT and the BT is not large (mean value of 6.3 vs. 6.9 MPa, respectively). Trying to discard the low values affected by possible misalignments, a truncated mean value (mean value of the 2/3 higher values) is shown in Figure 3. The truncated mean is slightly more similar, 7.0 vs 7.4 MPa for DT and BT, respectively.

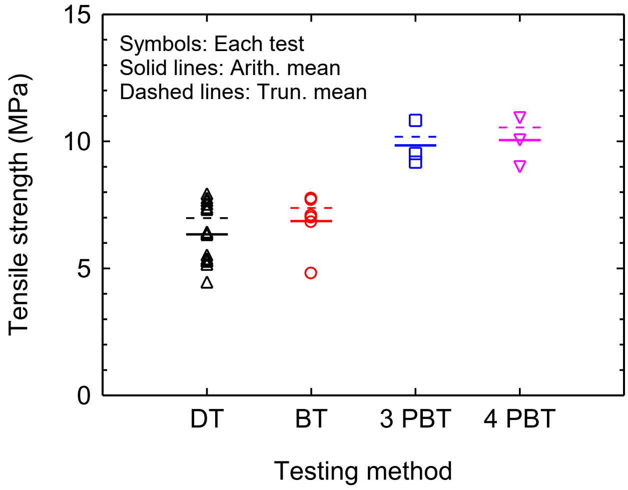

Figure 3. Tensile strength of Moleanos limestone obtained using different testing methods.

Bending tests give a much higher tensile strength, 10.2 and 10.5 MPa for the 3PBT and 4PBT, respectively. This is attributed to the stress gradient effect (e.g., Coviello et al. 2005), which is more notable in these samples of low thickness (30 mm of thickness). The 4 PBT has a zone of constant bending moment in the central part, while the 3 PBT reaches the maximum bending only in the central cross section. On the other hand, the application of the load in the 3 PBT may introduce some damage.

5 CONCLUSIONS

Measuring the tensile strength of rocks is crucial due to their susceptibility to tensile loading, a common cause of failure. Direct tensile testing, although the most accurate method, can be challenging and require precise conditions. Factors such as sample preparation, gripping, misalignments and stress concentrations tend to reduce the measured value. Therefore, indirect methods are often employed and several authors have presented comparisons between different methods.

The comparison presented here shows that DT results had slightly higher dispersity than BT, but the DT mean value was only a bit lower than that measured using BT (6.3 vs 6.9 MPa, a ratio of 0.91). On the other hand, bending tests yielded much higher tensile strength values (over 9 MPa in all the cases), highlighting the impact of the stress gradient effect, especially in low-thickness samples and when using linear elasticity until failure for the interpretation. In summary, while direct and indirect methods provide insights into rock tensile strength, careful consideration of specimen characteristics and testing conditions are essential for reliable results.

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