IMPROVEMENTS TO TENSILE STRENGTH MEASUREMENT OF HARD ROCKS

Mehdi Serati, David J Williams

School of Civil Engineering, The University of Queensland, Brisbane, Queensland, Australia

ABSTRACT

This paper, first, reviews some of the widely accepted testing techniques in the literature for the tensile strength measurement of rocks and investigates further their validity to hard and brittle rocks. Then, based on some preliminary studies, three improved testing techniques are introduced as potential alternative tensile strength test methods for hard and brittle rock-like geomaterials.

1 INTRODUCTION

Geomaterials commonly refer to both natural materials of geological origin (e.g. soil and rock), and manufactured and processed geo-like materials (e.g. bricks, crushed stone aggregates, asphalt, pavement, solid waste, dredged material, etc.). Hence, geomaterials cover a wide range of materials for which geotechnical parameters must be obtained to enable the reliable design of buildings and footings, highways and railways, tunnels, earthen embankments, open pit and underground mines. Although the literature is replete with test methods and standards to estimate the strength of geomaterials, many of these test methods have not been advanced for decades, rely on simple apparatus (when more advanced test methods and equipment are becoming available), and are inadequate for the requirements of modern infrastructure.

On the other hand, unlike metals, rocks and rock-like geomaterils are typically brittle and fracture without significant plastic deformation prior to failure. Rocks have also a large ratio of compressive to tensile strength, or so-called a high brittleness index (Zhang et al., 2016). That is, a great difference exists between the compressive and tensile strength values of rocks. This makes rocks, particularly hard and brittle rocks, extraordinarily weaker in tension than in compression or shear. Therefore, tensile fracturing of hard rocks can be abrupt and violent, leading to shattering without any pre-warning. Such explosion-like fractures in the field are commonly known as stress spalling or rock bursting, and have been reported frequently worldwide; e.g., in metal mines in North America (Feng, 2017). These catastrophic rock failures can jeopardise the safety of personnel, seriously damage rock structures, and shutdown operations temporarily or permanently. To avoid such unwanted brittle failure modes, reliable prediction of tensile crack initiation in hard and brittle rocks is must needed, although this has always been a major uncertainty. This study first reviews the application of some of the currently available tensile testing methods to hard and brittle materials. Then, three recent studies on the problem of brittle cracking in specimens of high brittleness index are reviewed which have revealed very promising outcomes. The observations suggest that the new studies can be used to determine the tensile strength of hard rocks for which the standard methods are deemed less effective.

2 BACKGROUND AND MOTIVATION

Tensile strength is the most critical design parameter of brittle materials in a wide range of engineering applications. The rock mechanics literature is almost exclusively replete with direct and indirect testing methods to estimate rock tensile strength. However, the direct test methods are notoriously too difficult and expensive for routine application to large numbers of specimens (Komurlu et al., 2017), hence indirect tests have been reported to offer the most desirable alternative. Among the indirect methods, the Brazilian test developed by Carneiro (Carneiro, 1943), the Ring test initially proposed in the late 1940s (Ripperger et al., 1947), and the point load test (PLST) are perhaps the most widely accepted methods with their initial applications trace back to concrete testing. The International Society for Rock Mechanics (ISRM), as well as the American Systems for Testing and Materials (ASTM) have also recognised these tests for use in practice and design (Ulusay, 2014; ASTM, 2016).

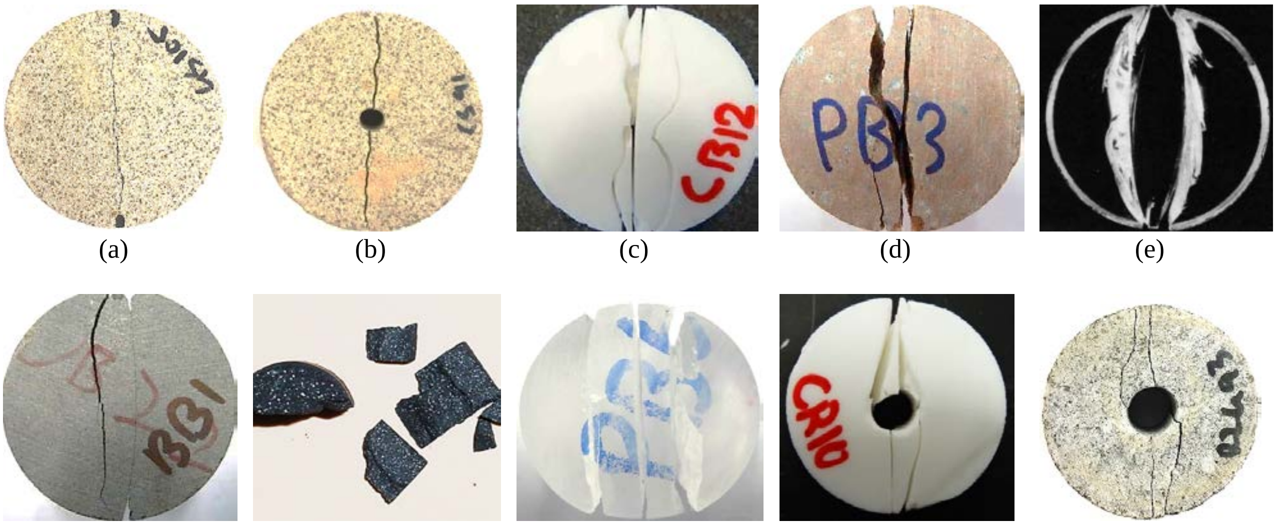
Both the Brazilian and the Ring tests simply involve compressing a disc specimen until it splits into two halves under tension. According to Griffith's strength criterion (Griffith, 1921), the Brazilian test is valid if the rupture forms a single straight tensile crack initiated at the centre of a solid disc. In case of the Ring test, test results are also valid if the rupture initiates at the two points on the boundary of the inner hole located on the diameter connecting the applied concentrated loads. However, reports indicate that when hard rocks (like granite and basalt) or any type of materials with a large brittleness index (e.g. ceramic, glass or diamond composites) are tested, the expected tensile breakage is always characterised by multiple cracks, inverse shear conical plugs and triple-cleft fractures (Serati et al., 2015; Komurlu et al., 2017). That is, test results deviate significantly from the standard recommendations and produce erroneous estimations of the actual tensile strength of the target materials, for which there is no definitive interpretation available. For instance, Erarslan and Williams (Erarslan et al., 2012b) carried out a series of Brazilian and direct tensile tests on Brisbane tuff specimens. From their results, it is evident that the Brazilian method can readily overestimate the material's tensile strength by 50%, when the tensile failure is accompanied by multiple tensile and/or shear cracks. This can also be readily seen in Figure 1 where both valid test results and unaccepted failures recorded are illustrated when the Brazilian and Ring tests are adopted with harder and stiffer materials. It is worth noting that all the tests in Figure 1 were conducted according to ISRM and ASTM recommendations, but the results for hard and brittle materials clearly demonstrate that it is impractical to follow the standard test methodologies in their entirety. In other words, the concentration of shear stresses developed in the vicinity of contacts always interferes with the expected single tensile breakage of test specimens through the formation of inverse shear conical plugs and multiple cracking, for which the actual causes are yet unknown.

Similarly, in a standard PLST, a rock specimen is subjected to a pair of concentrated loads and typically breaks into two or more pieces due to the propagation of induced tensile cracks (Ulusay, 2014). The force at failure (P) can be therefore correlated to the material's tensile strength (σ_t) according to the purely imperial Equation 1 (ISRM, 1985):

$$\sigma_t = \ (0.5\ to\ 1.5) \times I_s \tag{1}$$

where I_S is the point load strength index calculated as P/D^2, and D is the diameter of a point load specimen when loaded diametrically. However, given that the magnitude and the location of the maximum tensile stress induced in PLST is greatly affected by the size and shape of the tested specimen (Chau et al., 2001), Equation 1 is to be treated with great caution when the specimen's geometry differs (even slightly) from the standard recommendations. This in return limit the applicability of Equation 1 in practice (Serati et al., 2018).

Moreover, the recent work of the authors and colleagues (Serati et al., 2015; Masoumi et al., 2017; Serati et al., 2017) have further demonstrated that almost all available tensile strength testing methods when adopted for hard and brittle materials (particularly the most popular Brazilian and Ring tests) suffer from a non-unified mode of failure, brittleness variations and adverse effects from the size and shape of the test specimen. These adverse phenomena can generally result in an over-estimation of the material's tensile strength, which can cause unexpected collapse of rocks, excavations, foundations, and structures. Several solutions including the three-point loading test (Ulusay, 2014), testing of a spherically shaped specimen subjected to concentrated forces (Wijk, 1978), the double-punch test originally proposed in 1970 (Chen et al., 1972), the so-called flattened Brazilian disc (Wang et al., 2004), semi-circular bending test (Coviello et al., 2005), and strip loading of a Brazilian disc (Erarslan et al., 2012a) have therefore been proposed to address this issue, but interestingly none of them has been deemed a general solution applicable to a wide range of hard and brittle rocks. Motivated by such observations, the authors and colleagues have conducted some preliminary studies aimed at improving the current techniques and introducing alternative test methods, which are discussed below.



(a) (b) (c) (d) (e)

(f) (g) (h) (i) (j)

Figure 1: A valid (a) Brazilian, and (b) Ring test conducted with a medium-strength sandstone. Invalid Brazilian and Ring test results conducted on harder and more brittle materials including: (c) ceramic, (d) monzonite, (e) glass, (f) basalt, (g) thermally stable diamond composite, (h) polymethyl methacrylate (PMMA), (i) ceramic, and (j) Brisbane tuff.

3 ALTERNATIVE IMPROVED METHODS

3.1 TRUNCATED SPHEROIDAL SPECIMENS

In an initial study, funded by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), it was demonstrated that semi-prolate spheroidal (bullet-shaped) specimens can be conveniently used to determine the tensile strength of brittle stiff diamond-like composites (Serati et al., 2015). To this end, a series of experimental measurements and finite element (FE) numerical modelling were carried out to understand the fracture mechanism of the proposed bullet-shaped specimens made of a selected range of brittle materials including MACOR glass ceramic, graphite and thermally stable diamond composite (TSDC). The mechanical properties of the chosen materials were calculated first using the standard methods, i.e. the Brazilian test method, followed by testing of the bullet-shaped specimens. Experimental results showed that under a certain compressive test condition, stresses normal to the axisymmetric line in bullet-shaped specimens were in most places in tension and resulted in tensile fractures of the majority of the specimens (see Figure 2). Knowing the geometry, the failure force and the contact boundary conditions, FE numerical simulations of the experiments were conducted to determine the critical tensile stresses at which the specimens broke. From further dimensionless analyses of the problem, it was concluded that bullet profile specimens can be used to precisely determine the tensile bearing capacity of super hard materials where standard and conventional laboratory strength measuring tests - requiring coring, trimming - are not normally applicable. The proposed technique was also successfully adopted to explain the old, unsolved real-world problem of premature failures of CSIRO’s TSDC drilling elements, which have been trialled over the last decade in hard rock cutting operations (Serati, 2014).

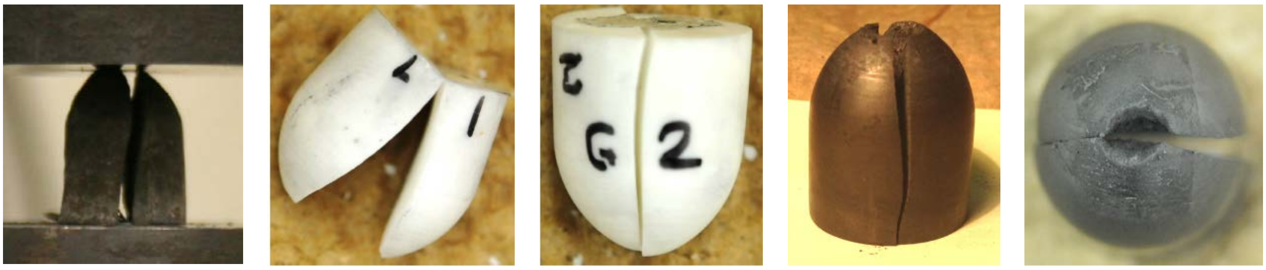
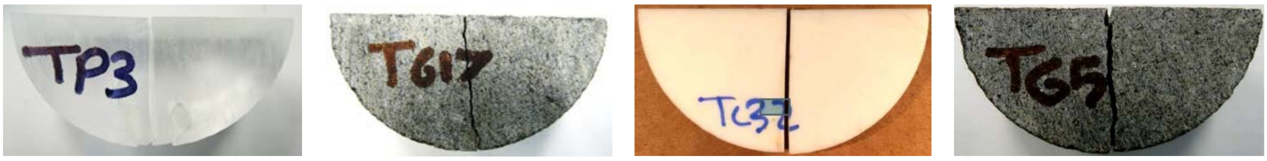


Figure 2: Tensile cracks in diamond, glass ceramic and graphite bullet-shaped samples (Serati et al., 2015)

3.2 TRUNCATED BRAZILIAN DISCS

Through a joint collaborative research grant between the University of Queensland (UQ) and UNSW funded by the Mining Education Australia (MEA), it was demonstrated that semi-cylindrical-shaped (truncated Brazilian disc) specimens can also be used to eliminate catastrophic crushing failure and multiple cracking in rocks of high brittleness index (see Figure 1). Brazilian specimens of a wide range of hard and brittle materials (including various types of rocks, polymers and glass-ceramics) were first cut across their diameter to form a flat end for load bearing. The truncated Brazilian discs were then loaded in direct contact with the machine platens under a constant loading rate. Contact conditions on the curved surface of the discs were carefully controlled by applying the load through steel loading arcs of different angle. In all the truncated discs, a single central crack resulting from indirect (induced) tensile stress was observed dividing the specimens into two roughly equal halves as shown in Figure 3. Through FE numerical modelling and high-speed photography of the fracture process, the rupture mechanism was further confirmed to be the result of an indirect tensile stress induced inside the specimens.

In other words, in both the bullet-shaped and the truncated disc test methods, it was proven that almost all tested specimens behave like a linear elastic material up to the ultimate failure load, indicating elastic-perfectly brittle rupture behaviour of the specimen under a dominant tensile mode of fracturing. That is, bullet-shaped and truncated specimens split into two perfect halves or quarter cylinders as a result of the propagation of predominantly a single tensile crack. The unwanted effect of high shear stresses at the loading points and the multiple cracking phenomenon, commonly found in the Brazilian and Ring tests discussed above, were therefore successfully eliminated. Nevertheless, although both methods have been only tested with limited hard rock-like materials, it is expected that the outcomes can be conveniently adopted for a wider range of harder and more brittle materials, including advanced ceramics, high strength concretes, natural and artificial bones and high-temperature superalloys.



(a) (b) (c) (d)

Figure 3: A single tensile crack observed in loaded truncated Brazilian disc specimens of brittle materials including polymethyl methacrylate (PMMA), granite, ceramic and basalt

2.2 POINT LOAD STRENGTH TEST

Unlike Brazilian and the Ring tests, where the initiation of the induced tensile crack is almost independent of testing conditions, the location of the maximum tensile stress in PLST is greatly affected by the loading conditions, geometry, size and shape of the tested specimen (Chau et al., 1996; Chau et al., 2001). However, due to the complex three-dimensional (3D) stress distribution involved, there exist very few theoretical solutions to study the effects of specimen shape on the critical value of stresses in PLST. Based on a three-dimensional elastic closed-form solution developed earlier by the authors (Serati et al., 2013; Serati et al., 2016), a new closed-form expression summarised in Equation 2 was derived to measure the maximum tensile stress (σ_t) at the centre of a finite isotropic solid cylinder when diametrically loaded on the middle of its curved surface, i.e. a loading condition similar to diametrical PLST.

$$\sigma_t = \frac{P}{D^2}(4 - 0.15\upsilon)\left(0.2 + 1.70e^{-5.5\frac{t}{D}}\right) \tag{2}$$

where P is the compressive force at the moment the core rock is split, D and t are the diameter and thickness of the point load specimen, respectively, and υ is the material’s Poisson's ratio. The validity of Equation 2 has also been experimentally examined in a recent study with a series of granite and Monzonite samples (see also Figure 4), but a more detailed numerical and laboratory investigation are required, which are currently underway. Unlike Equation 1, the proposed expression 2 accounts for the shape effect that has been ignored in previous studies, thus is expected to provide a more realistic estimation of the material’s tensile strength in a PLST.

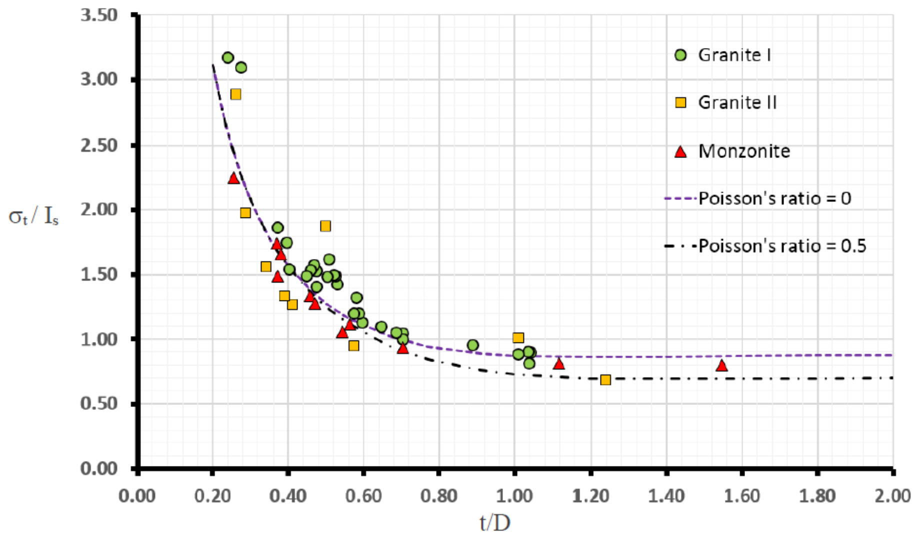


Figure 4: Normalized point load strength index values (I_s) by the Brazilian test results (σ_t) measured at different specimen shapes (t/D), and the theoretical predictions generated by Equation 2 for comparison.

4 CONCLUSION

Available direct or indirect laboratory tests for measuring the tensile strength of hard and brittle rocks and rock-like geomaterials (including the widely accepted Brazilian and Ring tests) may not be practical due to difficulties in following the standard recommendations entirely. New or improved approaches need to be therefore introduced since the available methods are not effective. This study briefly reports such difficulties and reviews some of the newly published techniques that aims to overcome this dilemma.

References

ASTM. (2016). 'D3967. Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens', *Annual Book of ASTM Standards, American Society for Testing and Materials, West Conshohocken, PA.*

Carneiro, FLLB. (1943). "A new method to determine the tensile strength of concrete." In *Proceedings of the Fifth Meeting of the Brazilian Association for Technical Rules, Third Section*, 126-9. ADINA R&D.

Chau, K. T. , and R. H. C. Wong. (1996). "Uniaxial compressive strength and point load strength of rocks." In *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 183-88. Pergamon.

Chau, K. T., and X. X. Wei. (2001). 'A new analytic solution for the diametral point load strength test on finite solid circular cylinders', *International Journal of Solids and Structures*, 38: 1459-81.

Chen, W. F. , and B. E. Trumbauer. (1972). 'Double-punch test and tensile strength of concrete', *Journal of Materials*, 7.

Coviello, A, R Lagioia, and R Nova. (2005). 'On the measurement of the tensile strength of soft rocks', *Rock Mechanics and Rock Engineering*, 38: 251-73.

Erarslan, N. , and D. J. Williams. (2012a). 'Experimental, numerical and analytical studies on tensile strength of rocks', *International Journal of Rock Mechanics and Mining Sciences*, 49: 21-30.

Erarslan, N., and D. J. Williams. (2012b). 'Experimental, numerical and analytical studies on tensile strength of rocks', *Int J Rock Mech Min Sci*, 49: 21-30.

Feng, Xia-Ting. (2017). *Rockburst: Mechanisms, Monitoring, Warning, and Mitigation* (Butterworth-Heinemann).

Griffith, Alan A. (1921). 'The phenomena of rupture and flow in solids', *Philos. Trans. R. Soc. Lond. A*, 221: 163-98.

ISRM. (1985). 'Suggested Method for Determining Point Load Strength ', *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 22: 51-60.

Komurlu, E., A. Kesimal, and A. D. Demir. (2017). 'Dog bone shaped specimen testing method to evaluate tensile strength of rock materials', *GEOMECHANICS AND ENGINEERING*, 12: 883-98.

Masoumi, H., M. Serati, D. J. Williams, and H. Alehossein. (2017). "Size Dependency of Intact Rocks with High Brittleness: A Potential Solution to Eliminate Secondary Fractures in Brazilian Test." In *51st US Rock Mechanics/Geomechanics Symposium (ARMA)*. San Francisco, US, 25-28 June.

Ripperger, E. A. , and N. Davids. (1947). 'Critical stresses in a circular ring', *Transactions of the American Society of Civil Engineers*, 112: 619-28.

Serati, M. (2014). 'Stiffness and strength of rock cutting and drilling tools – drag bit and roller disc cutters', The University of Queensland.

Serati, M. , H. Alehossein, and D. J. Williams. (2016). 'Theoretical treatment of disc cutters subjected to general cutting forces', *Journal of Engineering Mathematics*, 100: 141-65.

Serati, M., H. Alehossein, and D. J. Williams. (2015). 'Estimating the tensile strength of super hard brittle materials using truncated spheroidal specimens', *Journal of the Mechanics and Physics of Solids*, 78: 123-40.

Serati, M., H. Alehossein, and D. J. Williams. (2013). '3D Elastic Solutions for Laterally Loaded Discs: Generalised Brazilian and Point Load Tests', *Rock Mechanics and Rock Engineering*: 1-15.

Serati, M., H. Masoumi, D. J. Williams, and H. Alehossein. (2017). "Modified Brazilian Test for Indirect Measurement of Tensile Strength of Brittle Materials." In *51st US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association.

Serati, M., H. Masoumi, D. J. Williams, H. Alehossein, and H. Roshan. (2018). "Some New Aspects on the Diametral Point Load Testing." In *52st US Rock Mechanics/Geomechanics Symposium (ARMA2018)*. Seattle, Washington, USA.

Ulusay, Reşat. (2014). "The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014." In.: Springer.

Wang, Q. Z., X. M. Jia, S. Q. Kou, Z. X. Zhang, and P. A. Lindqvist. (2004). 'The flattened Brazilian disc specimen used for testing elastic modulus, tensile strength and fracture toughness of brittle rocks: analytical and numerical results', *International Journal of Rock Mechanics and Mining Sciences*, 41: 245-53.

Wijk, G. . (1978). 'Some new theoretical aspects of indirect measurements of the tensile strength of rocks', *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 15: 149-60.

Zhang, D. , P. G. Ranjith, and M. S. A. Perera. (2016). 'The brittleness indices used in rock mechanics and their application in shale hydraulic fracturing: A review', *Journal of Petroleum Science and Engineering*, 143: 158-70.