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Review scientific paper

Current Cognition of Rock Tensile Strength Testing By Brazilian Test

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Abstract

Tensile strength of intact rock materials has been determined by the indirect method more frequently than by the direct method. This paper presents a historical review of the development of the indirect method called the Brazilian test, comprising the period from 1943 to the present day. It stresses some aspects which are essential for interpreting the results of the Brazilian test due to the different degrees of stress during the testing and the direct method of determining tensile strength. The estimate of the direct tensile strength and the influence of sample saturation on the results of indirect tensile strength testing have been specifically elaborated.

Keywords

Tensile strength, indirect tensile strength, Brazilian test, rock mechanics

1. Introduction

Tensile strength of rock material is usually defined as the maximum tensile stress which can be endured by such a material. Rock material usually has a low tensile strength, which can be determined by direct and indirect methods of which the most famous is the Brazilian test. The direct testing procedure is carried out on the samples which require demanding processing conditions. Tensile stress is transferred to the ends of the samples using a cemented or glued steel plate with hooks on it (**Figure 1**). It is very important that the axis impact of the tensile matches with the axis of the sample without bending or torsion, i.e. other external impacts (**Hoek, 1964**). In order to ensure that the sample breaks at a specific point, it can be manufactured in the form of a dumbbell or dog – bone.

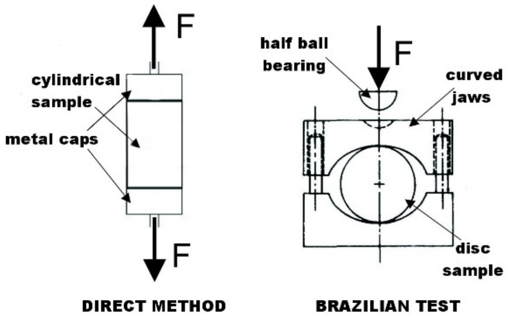

Figure 1. The principle of testing tensile strength by the direct method and the Brazilian test

Although deficiencies were observed due to the stress concentration at the ends of the sample and therefore a number of other ways of loading were designed, such as biaxial extension (**Brace, 1964**) and tension load converter (**Gorski, 1993; Klanphumeesri, 2010**), the International Society for Rock Mechanics has not changed its recommendations. These include the application of tensile stress by cemented caps on the end of the cylindrical sample. The diameter of the metal caps should not be less than 2 mm compared to the sample diameter and should be regularly glued. The ratio between the

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diameter and the height of the sample should be 2.5 to 3, whereas the sides should be smooth and without roughness larger than 0.3 mm. The bases must be aligned with no irregularities larger than 0.02 mm and should not deviate from perpendicularity to the axis of the sample of 0.001 radians, which is approximately 0.05 mm for the sample diameter of 50 mm. Tensile stress is applied continuously with a constant increase, so that the fracture occurs within about 5 minutes, or grows between 0.5 and 1 MPa/s. The direct tensile strength is calculated by dividing the maximum load applied to the sample by the initial cross-sectional area (**ISRM, 1978**). Due to the complexity of direct methods, particularly in the preparation of samples and applying the load, the Brazilian test, which indirectly determines tensile strength, is more frequently used in engineering practice (**Figure 1**). The justifiability of this method is based on the experimental fact that the majority of the rocks that are in the state of the biaxial stress break due to the exceeded tensile strength, in the conditions when one principal stress is tensile, and the second compressive, the size of which does not exceed three times the tensile stress (**Briševac, 2012**).

2. Historical overview of development of Brazilian test

The Brazilian test is a popular method of indirect determination of the tensile strength of intact rock material that has been the topic of a large number of research works and debates for many years regarding its accuracy and correct use. In the last 72 years, this method has attracted many researchers and accordingly its development can be divided into three phases. The first phase began in 1943 when Carneiro proposed the test methods to obtain tensile strength of concrete (**Carneiro, 1943**). It lasted until 1978 when the International Society for Rock Mechanics issued a recommendation for its determination on the rocks (**ISRM, 1978**). Afterwards, in the period from 1979 to 1991, the second phase was characterized by the use of the standardized method of the Brazilian test. The last phase started in 1991 and continues today. It is characterized by the improvement of the original testing method (**Wong and Jong, 2013**). The same three-phase division of Wong and Li is elaborated in this paper (**Li and Wong, 2013**).

From a chronological point of view, the creator of the indirect method is Carneiro (**1943**), who introduced a test method in order to obtain the value of tensile strength of concrete and created the formula (1) to calculate tensile strength of the sample in the form of a disc which is biaxially burdened compressively by plates with a width of 0.1 diameter of samples

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \tag{1}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm).

In two months, Carneiro overtook the Japanese researchers Akazawa (**1943**), who presented a very similar method, and because of the war, there was no contact between them. This method in intact rock material was applied for the first time by Berrenbaum and Brodie (**1959**).

Assuming that the material is homogeneous, linearly elastic and isotropic, Hondros (**1959**) performed a complete solution of the stress in the case when the load was distributed over the finite arcs with diametric compression, comprising both, the discs and the cylinders.

Hobbs (**1964, 1965 and 1967**) was engaged in calculations of tensile strength on several occasions. He calculated it by diametrical compression of a disk with a central hole (ring test). The obtained results were then compared with the results of the Brazilian test. He studied the influence of lamination of rock material on the tensile strength and concluded that the variations in strength approximately match with the variations according to the Griffith failure criterion. He pointed to the existence of the relationship between the tensile and compressive strength of rock and other alternative measurements in rock mechanics.

Generalizing the Griffith failure criterion Fairhurst (**1964**) studied the fracture of the samples of the Brazilian test. It was concluded that the fracture may appear at the distance from the disc centre in the case of small angles of disc loading on the materials of a low ratio between compression and tension. Fairhurst found out that the value of the tensile stress obtained by the Brazilian test is slightly lower than the real value.

Having analyzed the strain on irregular samples exposed to the pair of concentrated loadings in the three-dimensional photoelectric experiments, followed by the mathematical analysis of the results, Hiramatsu and Oka (**1966**) presented a new method of calculating the tensile strength for irregular samples. It was determined that the tensile strength of a rock could approximately be determined as the 0.9 part of the critical loading under which the sample broke, divided by the square of the distance between the loading points. However, the disadvantage of this method is the fact that the loading condition on such samples is neither simple nor universal but depends on the shape of the specific sample.

Colback (**1966**) found that the reason for such a small number of research works on direct tensile strength lies in the difficulties of preparing the samples and the fact that the incorrectly prepared cylindrical samples break outside the central part and thus create invalid results. Colback considered the Brazilian test as the acceptable solution for the increased number of research works. He used the corrected Griffith failure criterion theory in order to project the appearance of fracture in the disc sample of the Brazilian test. According to Colback, the fracture should start in the centre of the disc, in order to perform the correct test. Under certain circumstances, the fracture would start at the initial loading points, which would make the test invalid. He recommended the control of samples after each test, in order to determine the correctness of the fracture.

Jaeger and Hoskins (**1966**) and Hoskins (**1967**) alone compared the theoretical and experimental values determined for three different methods of measuring tensile strength, using compressive stress. It was found that the calculated value of the maximum tensile stress depends on the value of the uniaxial tensile strength of the material. Due to the high variability of tensile strength of the samples, even those of the same rock, it was recommended to test a larger number of samples.

Hudson (**1969**) compared two indirect methods, the Brazilian test and the ring test, and concluded that the tensile strength determined in such a way is a rather experimental characteristic, not the characteristic of the material.

Mellor and Hawkes (**1971**) measured tensile strength by means of the radial compression of the Brazilian disc for three types of rocks, two plastic materials, a glass material and an ice material, and the experimental results were compared with the theoretical expectations. To reduce the strain of the initial loading points, they designed the curved jaws for loading stress on the sample. The research proved that the Brazilian test is a suitable test for determining the values of uniaxial tensile strength.

Hudson and his associates (**1972**) observed that the fracture of the Brazilian disc appeared directly under the initial loading points only if flat steel plates are used in testing by means of controllable power test devices. The above stated authors recommend neither the Brazilian test nor the ring test for determining the tensile strength properties of such materials.

Barla and Innaurato (**1973**) experimentally and numerically investigated the suitability of the indirect methods of measuring tensile strength on anisotropic rock samples. They used two types of samples under different orientations along the axis of anisotropy. They proved that the experimental results can be appropriately explained by the finite element method.

Having studied the application of three-dimensional distribution of the stress on the problems with the strain and deformations in the plane, Wijk (**1978**) proved that the three-dimensional "correction" of the two-dimensional theoretical solution should be considered, even for rather thin samples in the case of the Brazilian test. These theoretical observations show that the interpretation of the indirect tensile test of rock materials is more difficult than was expected.

The team of researchers led by Yanagidani (**1978**) used strain gages for crack detection and noticed that the initial crack does not originate from the point of initiation of stress, but the zone of tensile stress. His results were important for valuation of the Brazilian test.

The International Society for Rock Mechanics (**ISRM, 1978**) adopted the standardized method of the Brazilian test to be used for indirect measuring of the tensile strength according to the formula (2). However, the method of direct measuring of the tensile strength still remains the main method used for determining the tensile strength of rock.

$$\sigma_{BTS} = 0{,}636\frac{F}{D \cdot t} \tag{2}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm).

Lajtai (**1980**) concluded that the tensile strength determined by the point load testing is lower than the values of tensile strength obtained by the Brazilian test and that the Brazilian test seemed to yield a more accurate definition of both the tensile strength and its variation of directions.

Sundaram and Corrales (**1980**) pointed out that assuming the same elastic characteristics of the tensile and compressive stress could result in the overestimation of values of the tensile strength of rocks obtained by the Brazilian test and emphasized the importance of considering separate elastic characteristics of the sample under tensile and compressive stress.

Pandey and Singh (**1986**) analyzed the characteristics of deformation in tensile stress and discovered that the tensile strength obtained by the Brazilian test was almost two times larger than the values obtained by the direct method. Accordingly, they claimed that tensile strength is actually an experimental characteristic, not the characteristic of the material.

Based on the study of the interdependence between the Block Punch Strength Index and the indirect tensile strength determined by the Brazilian test on the samples of breccia, calcarenite, dunite, gneiss, limestone, marble, sandstone and mudstone, a formula (3) was created to calculate the indirect tensile strength with the BP index (**Van der Schrier, 1988**).

$$\sigma_{BTS} = 0{,}4BPI - 0{,}4 \tag{3}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
BPI – block punch strength index (MPa)

In the statistical study carried out by Newman and Bennett (**1990**), it was confirmed that the ratio between the length and the diameter of the sample, as well as the stress rate, have a significant impact on the indirect tensile strength of sandstone. Andreev (**1991a, b**) revised the process of determining the tensile strength using the Brazilian test, concentrating on the formula and the conditions of the contact on the sample. It was determined that the fracture in the contact area of the sample does not appear if its modulus of elasticity is significantly different from the modulus of elasticity of the stress applicator. Contrary to the earlier opinion, it was concluded that the Brazilian test provides the corresponding values for the materials which perform brittle fractures. The following formula (4) for calculation of the indirect tensile strength of such materials is suggested:

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \cdot \left(n + \frac{3}{n} \right) \tag{4}$$

where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm),
n – ratio between the uniaxial compressive and tensile strength.

The development of information technology enabled more demanding research works. Accordingly, simulations of fracture by means of computer software were made possible. A two-dimensional numerical simulation was created, based on the research of initiation and the growth of a crack, using the Mohr-Coulomb's failure criterion (**Malan et al. 1994**).

The information age has also facilitated the calculation of complex mathematical problems, but also more complex laboratory measurements. After conducting the testing of the indirect tensile strength of the anisotropic type of rocks (4 types of sandstone), Chen and his associates (**Chen et al, 1998**) concluded that the method based on the elastic isotropic assumptions should not be used in the analysis of anisotropic rocks. They proved that the indirect tensile strength of anisotropic rocks is not constant but depends on the angle between the plane anisotropy axis and the load on the sample. Based on the Brazilian test, they developed the method of measuring elasticity constants, involving displacement measurements using strain gages that are glued at an angle of 45 ° relative to the axis of the load.

Exadaktylos and Kaklis (**2001**) presented the explicit expressions of strains and deformations at any point of radially loaded anisotropic circular disc proved that the proposed analytical solutions can be effectively used in the feedback analyses and as a tool for determining the elasticity and strength of rock. It is presented both, in the case before the published experimental results on schists and gneisses and in the case of their testing on marble.

Based on the conducted testing of samples of 23 rock types, Sulukcu and Ulusay (**2001**) published the formula (5) for calculating the indirect tensile strength using the corrected block punch strength index and the point load strength index with the following formula (6).

$$\sigma_{BTS} = 0{,}86 \cdot BPI_c \qquad (5)$$

$$\sigma_{BTS} = 2{,}3 \cdot I_{S(50)} \qquad (6)$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
BPI_c – corrected block punch strength index (MPa),
$I_{S(50)}$ – point load strength index (MPa).

Lavrov and Vervoort (**2002**) analyzed the impact of the friction force applied to the two opposite ports of stress distribution in the Brazilian test. They concluded that the distribution of stresses within the sample was slightly affected by the influence of friction in its ends.

After observing the acoustic effects caused by the test, the analysis of the Kaiser degradation effect due to increased deviation from the main strain between loading cycles in the Brazilian tests was presented. The analysis of discontinuous shifts was used to explain the experimental results (**Lavrov et al, 2002**).

Inhomogeneity of the material has a significant impact on the distribution of tensile stress along the axis of loading. In order to present this fact, the finite element method (FEM) for two-dimensional analysis of geomaterials was used. By means of this method, the inhomogeneities and microstructures of the samples were modelled (**Yue et al, 2003**).

The Chinese-Swedish researchers have designed a method that uses a flattened Brazilian disc. In one testing it would be possible to determine elasticity modulus, the indirect tensile strength (7) and the fracture toughness for brittle rocks. In order to enable the initiation of cracks in the centre of the sample, which is considered crucial for the validity of the test, the angle of loading must be larger than 20 ° (**Wang et al. 2004**).

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \cdot k_w \qquad (7)$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm),
k_w – coefficient which is closely related to the loading angle 2α, for $2\alpha=20^{\circ}$ $k= 0{,}9644$; $2\alpha=30^{\circ}$ $k= 0{,}9205$.

To determine the location of the crack, South African scientists conducted tests on the discs in which they drilled holes of different diameters and changed the position of the holes on the sample. After the experiment and simulation of the fracture they assumed that the fracture on the sample of the Brazilian test begins to spread in the vicinity of one of the sources of pressure on the disc (**Van De Steen et al., 2005**).

The Italian scientists, who experimented with various alternative ways of determining the value of tensile strength, concluded that it strictly depends on the selected test methods. They presented a critical assessment of some widely used laboratory techniques based on the experimental data obtained from the literature or their own ones and concluded that out of all the laboratory methods only the Brazilian test provides results similar to those obtained by the direct determination of tensile strength of soft rocks (**Coviello et al., 2005**).

Aydin and Basu (**2006**) observed that the weathering caused by the tropical climate weakens the microstructure of magmatic rocks. Accordingly, rock behaviour during tensile tests can be an indicator of the state of the microstructure and the weathering of rocks. Therefore, they created an indicator consisting of a 2 cm long strain gage located on the horizontal axis of the sample. In this way, they measured the size they called the Brazilian deformation index BDI on the basis of which the minimum variations caused by weathering can be obtained.

The stress analysis based on the three-dimensional finite element method 3D FEM showed the importance of the size and shape of the Brazilian disc. The conclusion was reached that the formula used in the past to calculate the indirect tensile strength is incorrect and must be corrected according to formula (8) in relation to the ratio of the thickness / diameter, especially in the case of patterns of increased thickness (**Yu et al., 2006**).

$$\sigma_{BTS} = \left(0{,}2621 \cdot k_R + 1\right)\frac{2F}{\pi \cdot D \cdot t} \tag{8}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm),
k_R – ratio between the thickness and diameter of the test specimen.

A team of Chinese scientists has designed an experimental method for obtaining a tensile modulus of elasticity. The method used strain gages glued on the samples during the Brazilian test. The analytical formula of the tensile elasticity modulus is represented by the expression (9). They found that the ratio between the tensile elasticity modulus and the compressive elasticity modulus is from 60 to 90% for marble, sandstone and limestone (**Ye et al., 2009**).

$$E_{BTS} = A_T \cdot E_S \tag{9}$$

Where:
E_{BTS} - tensile elasticity modulus (MPa),
A_T – correction coefficient which can be calculated from formula (10),
E_S – splitting elastic modulus which can be calculated from formula (11).

$$A_T = \left(1 - \frac{D}{t} \cdot \arctan\frac{2t}{D}\right) \cdot \left(1 - \nu\right) + \frac{2D^2 \cdot \left(1 + \nu\right)}{4t^2 \cdot D^2} \tag{10}$$

$$E_S = \frac{0{,}5\sigma_t}{\varepsilon_t} \tag{11}$$

Where:
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm),
ν – Poisson's ratio,
σ_t – maximum stress in test (MPa),
ε_t – the strain related to $\sigma_t/2$ in the stress–strain curve.

The analysis of the impact of the initial cracks on the distribution of stress has led to modelling by the Boundary Element Method BEM, i.e. the simulation process of the appearance and spreading of the cracks on the sample exposed to indirect tensile stress. The analyses of the models show that the stress distribution is only slightly affected by the friction between the jaw and the sample.

However, the appearance and spreading of cracks produced by the stress field is very different compared to the situation when the rock material is continuous, homogeneous, isotropic and elastic. It is considered that the analysis of the deformation of the sample along the diameter perpendicular to the load direction allows a direct determination of the tensile strength in the way that it is indicated by the point where the curve of the stress and malformation is perpendicular to the loading direction (**Lanaro et al., 2009**).

The stress analysis by the 3D FEM Method, assuming that the test materials are continuous, homogeneous and isotropic elastic, has enabled the production of a modified version of the Brazilian test.

Two special spacers are placed on the points of the initial loading, in order to reduce the stress concentration. This modification was introduced as it was considered that the original version of the Brazilian test significantly underestimates the tensile strength of the test material. They suggested that the indirect tensile strength should be calculated by the expression (12) for brittle rocks (**Yu et al., 2009**).

$$\sigma_{BTS} = \frac{2k_S \cdot F}{\pi \cdot D \cdot t} \tag{12}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
F – applied load (kN),
D – diameter of the tested sample (mm),
t – thickness of the tested sample (mm),
k_S – coefficient which relates to the state of stress in the point of initiation, and its best value is 1,11.

Tavallali and Vervoort (**2010a, b**) presented the importance of the orientation layers, i.e. anisotropy in tensile strength and the crack patterns in the Brazilian test. They observed three different types of cracks in the specific stratified sandstone from the south of Belgium and called them layer activation, central fractures, and non-central fractures. They described the effect of the size and shape of grain and mineral composition on tensile strength established by the Brazilian test.

Greek scientists published the papers stating a complete explanation of stress and displacement in the Brazilian disc under the evenly distributed radial load. However, the solution was presented under the assumption that the sample material is homogeneous, isotropic and linearly elastic. They studied the effect of evenly distributed shear stress at the points of loading. They noticed that the fracture first started at the edge of the initial points and then in the middle of the sample (**Markides et al., 2010 and 2011**).

Australian scientists presented the results of the experimental research on the relationship between the strain and the malformation of the Brisbane tuff samples which were loaded in two different ways. The first one was a sinusoidal cyclic loading and the second one was a cyclic loading with the increasing mean level. They found that the indirectly measured tensile strength was reduced by 33-37% under such conditions of performing the Brazilian test (**Erarslan and Williams, 2012**). The loading impact was compared on the samples of Brisbane tuff by means of the standard jaw with various loading arc angles of the sample. Besides the experimental tests, numerical simulations were performed too. The obtained results showed that the best geometry of loading to is $2\alpha = 20° - 30°$ along the arc of the sample (**Erarslan et al., 2012**).

Markides and Kourkoulis (**2012**) analysed the components of stresses in the samples of the Brazilian disc. The samples were tested under four different types of loading: loading at one point, evenly distributed radial pressure, sinusoidal loading, parabolic loading pressure. The parabolic loading proved to be the best one. The disadvantage of such an analysis is the fact that it was carried out with the presumption of linear elasticity, ignoring the influence of shear.

Indian scientists created a formula (13) for the calculation of the indirect tensile strength for granite, schist and sandstone, in order to improve the possibilities of the BP test. According to their research, the interdependence of the indirect tensile strength determined by the Brazilian test is higher with the corrected block punch strength index, determined by the point load strength index (**Mishra and Basu, 2012**).

$$\sigma_{BTS} = 0{,}35 \cdot BPI_c + 3{,}69 \tag{13}$$

Where:
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
BPI_c – corrected block punch strength index (MPa).

Kazareni (**2013**) presented a model based on the discontinuum which simulates the tensile and compressive failure of sandstone. The model reproduces the rock material in a better way, which is a dense group of irregular and distorted particles interacting at their borders. Kazareni concluded that such a way of modelling can be used to describe the relationship between microstructural and macro properties of materials.

Li and Wong (**2013**) published a review of the performed research works related to the Brazilian test and conducted a numerical analysis, having created the elastic model in the FLAC 3D program. By concentrating on the starting point of crack, they concluded that the starting point may be located near the points of loading in the moment when the tensile malformation meets the critical criterion of malformation, and that it may also be located in the centre when the tensile stress meets the maximum tensile strength criterion.

The recording with high-speed cameras was applied during the testing of indirect tensile strength under static and dynamic loading with granite samples for research purposes of the underground objects. Four ways of fracture patterns were observed: a diametrical tensile fracture, a central fracture with small wedges at the points of loading, a central fracture with a crushed zone and a fracture with the initiation from the shearly damaged frame zones. Accordingly, the authors recommended high-speed cameras to be used in the analysis of the correctness of fracture patterns as the usual optical analysis can be misleading (**Zhou et al., 2014**).

Turkish scientists have made the evaluation of indirect tensile strength by testing it with different types of jaws used to apply a pressure load on the sample. Their work shows that different materials react differently to loading and that the same type of jaw cannot be used for all the materials (**Kömürlü and Kesimal, 2015**). A disadvantage of their work may lie in the fact that only few tests were performed per individual material and the type of jaw, which are sometimes 4.

Recently, a team of the Chinese scientists presented a proposal for changes of the formula calculating the indirect tensile strength. In their opinion, Poisson's ratio was the most significant factor, including the angle of loading and the ratio of thickness and radius. They found that an increase in Poisson’s ratio and a smaller angle reduces the appearance of the central initiation of cracks. Using the Griffith criterion, they modified the formula in accordance with the recommended range of values. The formula (14) has been adjusted to the previous studies, numerically and experimentally (**Lin et al., 2015**).

$$\sigma_{BTS} = -(1{,}027 + 0{,}108\nu - 0{,}014\alpha) \cdot \frac{F}{\pi \cdot r \cdot t} \tag{14}$$

Where:

σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
ν – Poisson’s ratio,
α – half of the loading angle,
F – applied load (kN),
r – radius of the tested sample (mm),
t – thickness of the tested sample (mm).

According to the available literature, testing of tensile strength with the Brazilian test on the materials on the territory of Croatia comprises various studies conducted for the purpose of performing geotechnical structures, especially road infrastructure (**Šestanović et al., 1993, Pollak, 2002**), as well as the tests for the purpose of dimensioning underground chambers upon underground exploitation of dimension stone (**Hrženjak et al., 2008**). Indirect tensile strength was investigated under the force in the direction perpendicular to the surface layer and in the case of the force in the direction parallel with bedding planes of the A, E and F deposits of dimension stone "Korenići" in Istria (**Dobrilović et al. 2010**). The influence of saturation on the indirect tensile strength of gypsum (**Macenić, 2011**) and limestone (**Čajić, 2015**) was also investigated.

It is important to emphasize that there are differences between the results of the direct and the indirect measurements of tensile strength by the Brazilian test, which can be seen in **Table 1**, where the data was collected from the relevant literature and calculated the ratio $\sigma_{BTS} / \sigma_{UTS}$. However, some materials, e.g. limestone, partially show a reverse trend of the relations $\sigma_{BTS} / \sigma_{UTS}$, compared to the collected data. The limestone types Indiana and Saraburi show that the Brazilian test overestimates their strength, while limestones collectively show that the test underestimates their strength.

Table 1: The ratio of tensile strength determined by the direct method and the indirect tensile strength determined by the Brazilian test

Rock type	σ_{UTS}	σ_{BTS}	$\sigma_{BTS}/\sigma_{UTS}$	References
Bowral trachyte	13,72	12,00	0,87	Jaeger (1967)
Trachyte	13,7	7,7	0,56	Perras and Diederichs (2014)
Vitosha syenite	20,50	21,05	1,03	Andreev (1991a)
Barre granite	13,45	14,34	1,07	Mellor and Hawkes (1971)
Granite	6,3	10,3	1,63	Perras and Diederichs (2014)
Carrara marble	6,90	8,72	1,27	Jaeger (1967)
Ufalei marble	5.90 ± 2.66	6.90 ± 1.24	1,17	Efimov (2009)
Saraburi marble	6.33 ± 0.62	8.02 ± 0.25	1,27	Fuenkajorn and Klanphumeesri (2011)
Marble	7,5	10,1	1,35	Perras and Diederichs (2014)
Gneiss	8,2	9,8	1,2	Perras and Diederichs (2014)
Quartzite	16,3	13,0	0,8	Perras and Diederichs (2014)
Schist	13,3	11,8	0,89	Perras and Diederichs (2014)
Shale	5,6	5,9	1,05	Perras and Diederichs (2014)
Grey gypsum	1,75	1,99	1,14	Andreev (1991a)
White gypsum	1,42	1,29	0,91	Andreev (1991a)
Gosford sandstone	3,59	3,72	1,04	Jaeger (1967)
Phu Phan sandstone	6.49 ± 0.22	10.68 ± 0.70	1,65	Fuenkajorn and Klanphumeesri (2011)
Sandstone	5,1	9,5	1,86	Perras i Diederichs (2014)
Gravina calcarenite	0.69 ± 0.03	0.64 ± 0.10	0,93	Coviello et al. (2005)
Indiana limestone	5,86	6,21	1,06	Mellor and Hawkes (1971)
Saraburi limestone	9.31 ± 0.65	10.90 ± 0.19	1,17	Fuenkajorn and Klanphumeesri (2011)
Limestone	7,1	6,0	0,85	Perras and Diederichs (2014)
Dolomite	5,7	8	1,4	Perras and Diederichs (2014)

σ_{UTS} – direct tensile strength; σ_{BTS} - indirect tensile strength determined by the Brazilian test

2. Estimating tensile strength with other characteristics

According to Hoek (**1966**) it is usually considered that a tensile strength is one tenth in size compared to the compressive strength and can be calculated by the expression (15).

$$\sigma_{UTS} = -\frac{\sigma_{UCS}}{10} \tag{15}$$

Where:
σ_{UTS} – direct tensile strength (MPa),
σ_{UCS} – uniaxial compressive strength (MPa).

Zhang (**2005**) suggested that the tensile strength for a particular rock material can be calculated by the formula (16). The same author stated the expression (17) for calculating tensile strength through point load strength index.

$$\sigma_{UTS} = -k_m \cdot \sigma_{UCS} \tag{16}$$

$$\sigma_{UTS} = -1{,}5 \cdot I_{S(50)} \tag{17}$$

Where:
σ_{UTS} – direct tensile strength (MPa),
σ_{UCS} – uniaxial compressive strength (MPa),
k_m – coefficient which is approximately from 0.03 to 0.24 depending on the type of rock,
$I_{S(50)}$ – point load strength index (MPa).

After reviewing the relevant literature Perras and Diederichs (**2014**) concluded that the largest error occurs upon estimating through uniaxial compressive strength, whereas there is a less error if the Hoek-Brown constant is used, m_i according to the expression (18).

$$\sigma_{UTS} = -\frac{\sigma_{UCS}}{m_i} \tag{18}$$

Where:
σ_{UTS} – direct tensile strength (MPa),
σ_{UCS} – uniaxial compressive strength (MPa),
m_i – Hoek-Brown constant.

Using the measured value of crack initiation (CI) to estimate the direct tensile strength according to the expression (19) provides better results than the correlation over the uniaxial compressive strength. However, such an estimate depends on the type of rock, too. The expression (19) should in the future be modified according to the material properties (**Perras and Diederichs, 2014**).

$$\sigma_{UTS} = -\frac{CI}{k_\beta} \tag{19}$$

Where:
σ_{UTS} – direct tensile strength (MPa),
CI – crack initiation (MPa),
k_β – coefficient which is 8 according to the original Griffith theory and can be as high as 12 according to the modified formulation of the Griffith theory.

Based on the literature in the field of determining the tensile strength, Swiss scientists generally concluded that the direct tensile strength is difficult to estimate on the basis of other laboratory tests. They concluded that the estimate of the direct strength through indirect tensile strength determined by the Brazilian test depends on the type of rock and recommended to be performed according to the formula (20) to improve the estimate (**Perras and Diederichs, 2014**).

$$\sigma_{UTS} = \sigma_{BTS} \cdot k_T \tag{20}$$

Where:
σ_{UTS} - direct tensile strength (MPa),
σ_{BTS} - indirect tensile strength determined by the Brazilian test (MPa),
k_T – correction coefficient which is approximately 0.9 for metamorphic, 0.8 for magmatic and 0.7 for sedimentary rocks.

3. Influence of saturation of samples on their indirect tensile strength

The issue of the influence of saturation on the tensile strength was only generally analysed in older research. Dube and Singh (**1972**) investigated the influence of humid climate on the indirect tensile strength of sandstone using the Brazilian test. It was discovered that the porous sandstones and those which have clay minerals are sensitive to the reduction of the tensile strength to the most.

Vutukuri (**1974**) conducted more extensive research, dealing with alternative methods of determining the tensile strength. He used the ring test for determining the tensile strength of limestone samples and examined the dependence of the effects of various types of liquids on the value of the tensile strength of limestone. The saturation in the period of 20 hours was carried out with: water, glycerine, ethanol, nitrobenzene, and several organic liquids. He found that the increase in the dielectric constant and surface tension of the liquid reduces the tensile strength of limestone.

Ojo and Brook (**1990**) examined the uniaxial compressive strength and the direct tensile strength of sandstone with a different degree of saturation. They found that both strengths decrease with an increasing degree of saturation, and the ratio between the uniaxial compressive strength and the direct tensile strength is larger in the dry state than in the saturated state. They stated that the decreased strength due to the saturation effect is more present in the direct tensile strength than the uniaxial compressive strength.

In view of more recent research works, the paper published by the team of Chinese scientists should be pointed out. They studied the effect of saturation of the samples with water on the indirect tensile strength of gneiss, marble and sandstone. The results showed that all of these rocks have a lower tensile strength at saturation compared to their dry state. The tests were performed by the Brazilian test and the ring test. It was concluded that the ring test shows slight differences of strength between dry and saturated samples (**You et al., 2011**).

Singaporean scientists studied the effect of saturation on the indirect tensile strength of synthetic gypsum, using high-speed cameras. The results show a rather high decrease of strength, half of the strength in the dry state after just a week of saturation. The recordings made with high-speed cameras show that the initial cracks in the majority of samples appeared in the centre, and that there is a difference between the way the fracture appeared in dry and saturated samples. Dry samples fractured after only one initiation and the crack was spreading rather quickly, whereas saturated samples had more initial cracks and slowly developed a primary tensile crack (**Wong and Jong, 2013**).

4. Discussion

The reason for a large number of the published papers regarding the Brazilian test is the fact that the indirect method, due to its constant development, has simplified the process of determining tensile strength of intact rock material. It has become possible to conduct a large number of testing procedures with a simple preparation of the samples, compared to the previous period when the preparation of samples was rather complicated and demanding. Tensile strength is an important characteristic of a specific material due to the fact that it is difficult to observe the conditions of fracture without it. Taking into consideration this characteristic, Griffith (**1921**, **1925**) introduced the criterion of strength for brittle materials. Afterwards, such a criterion was used in the rock mechanics in its original and modified forms, suggested by McClintock and Walsh (**1962**). A large number of papers on the Brazilian test comprises this criterion (Hobbs, **1964**, **1965** and **1967**; Fairhurst **1964**; Colback, **1966**; Linetal, **2015**). Although other criteria are more frequently used today, the area of tensile strength is modified according to Griffith, as it was done, e.g. by Hoek and Martin (**2014**) based on the conclusions stated in the paper by Fairhurst (**1964**).

The simple processing of samples enables a quick experimental check-up of the theoretical presumptions and their numerical analyses (Hiramatsu and Oka, **1966**; Barla and Innaurato **1973**; Sundaram and Corrales **1980**; Lavrovetal, **2002**; Yue et al., **2003**; Yu et al., **2006**; Lanaro et al**., 2009**; Yu et al., **2009**; Markides and Kourkoulis, **2012**; Li and Wong, **2013**;). However, the sensitivity to the testing conditions requires a careful explanation of the material behaviour during the testing and finding the solutions for removal of the flaws (Hobbs, **1964**, **1965**, **1967.**; Hudson, **1969**; Hudson et al., **1972**; Yanagidani et al., **1978**; Lajtai, **1980**; Pandey and Singh, **1986**; Newman and Bennett, **1990**; **Coviello et al., 2005**; Aydin and Basu, **2006**; Tavallali and Vervoort, **2010a, b**; Erarslan and Williams, **2012**).

In view of the various results obtained on the same type of rock, the previous research works mostly comprised anisothropy (Barla and Innaurato, **1973**; Chen et al **1998**; Exadaktylos and Kaklis, **2001**; Tavallali and Vervoort **2010a,b**). In the future it is expected that more attention will be paid to other differences among the specific types of rock materials, such as the petrographic characteristics, for example.

In view of the available references (Table 1), no general trend in the ratio between the direct and indirect tensile strengths for all the types of materials can be observed. Actually, the same materials on various locations can have a different ratio between the direct and indirect tensile strengths. Due to practical engineering needs, such an issue requires more attention. Accordingly, the Brazilian test should be applied on each direct testing of tensile strength in the future, in order to determine the ratio for each tested material.

Further development of the methods for estimating tensile strength in other laboratory testings is not expected as long as it is possible to determine the indirect tensile strength in a simple way by means of the Brazilian test, which also includes the estimate of the direct tensile strength. However, in the future it will be necessary to determine the correction coefficients according to the types of materials more precisely, as suggested in the paper by Perras and Diedrichs (**2014**). A relatively small number of papers on the effects of saturation has not provided the answer to the question how water actually affects the strength reduction. The issue of the water effect upon the indirect testing of tensile strength by the Brazilian test on the change of the cohesion or friction in the tested material has still remained open. The classification of the tested materials according to their mineralogical and petrographic characteristics, including the testing in dry and saturated conditions, can contribute to better comprehend this issue.

5. Conclusion

A large number of papers were made for the scientific purposes and they did not have any practical application. Accordingly, there is actually a rather small number of papers which may be used to improve the Brazilian test.

The standardization of the procedures using more expensive and more sophisticated equipment is not expected in the future, despite the fact that it would improve the testing procedures.

Therefore, it is necessary to determine more precisely the correction coefficients for the estimate of direct tensile strength by the Brazilian test for all types of materials, in order to obtain the optimum results.

Further research works on indirect tensile strength should be focused on the testing of the effect of saturation on various types of rock materials, including the determination of the relationship between the indirect and direct tensile strengths, due to the fact that this would have a practical purpose in engineering.

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Sadašnje spoznaje o ispitivanju vlačne čvrstoće stijena uporabom brazilskoga testa

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Sažetak

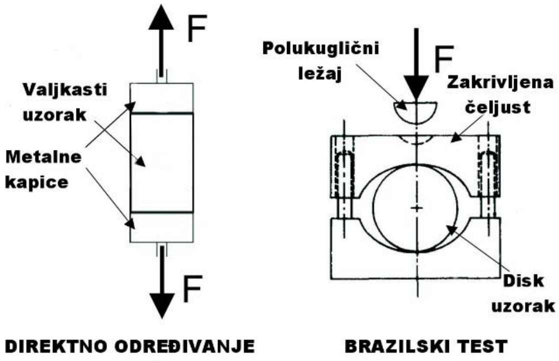
Vlačna čvrstoća u mehanici stijena svojstvo je koje se znatno češće određuje indirektno (neizravno) nego direktno (izravno). U ovome radu prikazan je povijesni pregled razvoja indirektne metode ispitivanja zvane brazilski test od njezina nastanka 1943. god. do današnjih dana. Upućuje se na neke aspekte koji su bitni za tumačenje rezultata brazilskoga testa zbog različitoga stanja naprezanja prilikom toga ispitivanja i direktnoga postupka za određivanje vlačne čvrstoće. Posebno je obrađena procjena direktne vlačne čvrstoće i utjecaj saturacije uzoraka na rezultate ispitivanja indirektne vlačne čvrstoće.

Ključne riječi

vlačna čvrstoća, indirektna vlačna čvrstoća, brazilski test, mehanika stijena

1. Uvod

Vlačna čvrstoća stijenskoga materijala obično se definira kao najveće vlačno naprezanje koje taj materijal može izdržati. Stijenski materijal obično ima nisku vlačnu čvrstoću, a njezino određivanje može se provesti direktnim i indirektnim postupcima od kojih je najpoznatiji brazilski test. Direktni postupak ispitivanja provodi se na uzorcima za koje vrijede zahtjevni uvjeti obrade. Vlačno naprezanje prenosi se na krajeve uzoraka pomoću metalnih kapica s kukama na sebi (**slika 1**). Najvažnije je da se os djelovanja vlačne sile podudara s osi uzorka bez savijanja ili torzije, odnosno drugih vanjskih utjecaja (**Hoek, 1964**). Kako bi se osiguralo da se uzorak slomi na određenome dijelu, on se može izraditi u obliku utega ili u obliku kosti (engl. *dumbbell*, *dog-bone*).



Slika 1: Princip testiranja vlačne čvrstoće direktnom (izravnom) metodom i brazilskim testom

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Iako su uočeni nedostatci zbog koncentracije naprezanja na krajevima uzorka te su zbog toga osmišljavani razni drugi načini nanošenja naprezanja poput dvoosnoga produženja (**Brace, 1964**) i pretvornika vlačnoga u tlačno opterećenje (**Gorski, 1993; Klanphumeesri, 2010**), Međunarodno društvo za mehaniku stijena nije promijenilo svoje preporuke. One uključuju nanošenje vlačnih naprezanja putem zalijepljenih kapica na valjkasti uzorak. Kapice ne smiju biti manje, a niti veće od 2 mm u odnosu na promjer uzorka te moraju biti zalijepljene prikladnim ljepilom. Uzorci moraju imati omjer promjera i visine od 2,5 do 3, a plašt mora biti ravan i gladak bez hrapavosti veće od 0,3 mm. Baze moraju biti poravnane bez nepravilnosti većih od 0,02 mm te ne smiju odstupati od okomitosti u odnosu na os uzorka više od 0,001 radijan, to je približno 0,05 mm za promjer uzoraka od 50 mm. Vlačno se naprezanje nanosi kontinuirano s konstantnim prirastom tako da se lom dogodi otprilike unutar 5 min ili s prirastom između 0,5 i 1 MPa/s. Direktna vlačna čvrstoća dobije se dijeljenjem najveće ostvarene vlačne sile prilikom loma s početnom površinom poprečnoga presjeka uzorka (**ISRM, 1978**). Zbog zahtjevnosti direktne metode, posebno u pripremi uzoraka i nanošenja opterećenja, puno se češće u inženjerskoj praksi primjenjuje brazilski test (**slika 1**) kojim se indirektno određuje vlačna čvrstoća. Opravdanost ovoga postupka temelji se na činjenici utvrđenoj eksperimentom da se većina stijena koje se nalaze u stanju dvoosnoga naprezanja najčešće lomi uslijed prekoračenja vlačne čvrstoće, u uvjetima kada je jedno glavno naprezanje vlačno, a drugo tlačno, s veličinom koja po iznosu ne prelazi trostruku vrijednost vlačnoga naprezanja (**Briševac, 2012**).

2. Povijesni pregled razvoja brazilskoga testa

Brazilski test popularna je metoda indirektnoga određivanja vlačne čvrstoće intaktnoga stijenskog materijala koja je kroz povijest prošla mnoga istraživanja i mnoge debate o svojoj točnosti i ispravnoj uporabi. U protekle 72 godine ova metoda privlačila je brojne istraživače te njezin razvoj možemo podijeliti u tri etape. Prva etapa počinje 1943. godine Carneirovim predlaganjem ispitne metode za dobivanje vlačne čvrstoće betona (**Carneiro, 1943**) i traje sve do 1978. godine, kada Međunarodno društvo za mehaniku stijena izdaje preporuku za njezino određivanje na stijenama (**ISRM, 1978**). Nakon toga, od 1979. do 1991. godine, proteže se druga etapa koju karakterizira standardizirana metoda brazilskoga testa, dok posljednja etapa počinje 1991. godine te traje još i danas, a karakterizira ju intencija nadogradnje izvorne metode ispitivanja (**Wong i Jong, 2013**). Istu troetapnu podjelu Wong detaljnije razrađuje s Lijem (**Li i Wong, 2013**) te je takva podjela zadržana i u ovome radu.

Kronološki gledano idejni je začetnik indirektne metode Carneiro (**1943**) koji je predložio ispitnu metodu kako bi dobio vrijednosti vlačne čvrstoće betona te je izveo jednadžbu (1) za računanje vlačne čvrstoće uzorka u obliku diska koji se dvoosno opterećuje tlačno pločama širine 0,1 promjera uzorka.

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \tag{1}$$

gdje je:
σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)
F – sila sloma uzorka (kN)
D – promjer uzorka (mm)
t – debljina uzorka (mm).

Carneiro je za dva mjeseca pretekao japanskoga istraživača Akazawu (**1943**) koji je predstavio vrlo sličnu metodu, a zbog rata nije bilo kontakata između njih dvojice. Prvu primjenu ove metode na intaktnome stijenskom materijalu proveli su Berrenbaum i Brodie (**1959**). Pretpostavljajući da je materijal homogen, linearno elastičan i izotropan, Hondros (**1959**) izvodi kompletno rješenje naprezanja u slučaju kada je opterećenje distribuirano preko krajnjih lukova dijametralnom kompresijom, kako za disk, tako i za cilindar.

Hobbs (**1964, 1965 i 1967**) se u više navrata bavio vlačnom čvrstoćom te ju je računao pomoću radijalnoga naprezanja diska s rupom u središtu, tako dobivene rezultate uspoređivao je s rezultatima brazilskoga testa. Proučavao je i utjecaj laminiranosti stijenskoga materijala na vlačnu čvrstoću te zaključio kako se varijacije čvrstoće približno podudaraju s varijacijama koje predviđa Griffithov kriterij loma. Pokazao je postojanje odnosa između vlačne i tlačne čvrstoće stijena te drugih alternativnih mjerenja u mehanici stijena.

Fairhurst (**1964**) je generalizirajući Griffithov kriterij loma proučavao lom uzoraka brazilskoga testa. Zaključuje da se lom može dogoditi dalje od središta diska za male kutove nanošenja naprezanja na disk kod materijala koji imaju nizak odnos tlačnoga i vlačnoga naprezanja. Uočio je da je vrijednost vlačnoga naprezanja dobivena brazilskim testom nešto niža od stvarne.

Analizirajući naprezanje na nepravilnim uzorcima koji su izloženi paru koncentriranih opterećenja kod trodimenzionalnih fotoelektričnih eksperimenata te provodeći matematičku analizu rezultata, Hiramatsu i Oka (**1966**) prezentirali su novu metodu izračuna vlačne čvrstoće za nepravilne uzorke. Utvrđeno je da bi se vlačna čvrstoća stijene mogla približno odrediti kao 0,9-i dio kritičnoga opterećenja pod kojim je ispitni uzorak slomljen, podijeljeno s kvadratom udaljenosti između točaka opterećenja. Međutim, nedostatak je te metode u tome što stanje naprezanja na takvim uzorcima nije jednostavno i univerzalno, već je ovisno o obliku samoga uzorka.

Colback (**1966**) je primijetio kako je razlog maloga broja ispitivanja direktne vlačne čvrstoće u poteškoćama kod pripreme uzoraka te nepravilno pripremljeni valjkasti uzorci pucaju izvan srednjega dijela i tako čine ispitivanja nevaljanima. Držao je brazilski test prihvatljivijim rješenjem za povećanje broja ispitivanja. Kako bi predvidio pojavu loma na uzorku brazilskoga diska, primjenjivao je izmijenjenu Griffithovu teoriju loma. Tvrdio je da lom mora započeti u središtu diska kako bi test bio valjan. Pod određenim uvjetima lom bi se počeo pojavljivati kod inicijalnih točaka opterećenja, a to bi ispitivanje činilo nevaljanim. Preporučio je pregled uzoraka poslije svakoga ispitivanja kako bi se utvrdila ispravnost sloma.

Jaeger je zajedno s Hoskinsom (**1966**) te samostalno (**1967**) sudjelovao u usporedbi teorijskih i eksperimentalnih vrijednosti za osmišljene tri različite metode mjerenja vlačne čvrstoće uz primjenu tlačnih naprezanja. Otkrio je kako je izračunana vrijednost maksimalnoga vlačnog naprezanja ovisna o vrijednosti jednoosne vlačne čvrstoće materijala. Zbog velike varijabilnosti vlačne čvrstoće uzoraka, koji su čak i od iste vrste stijene, preporučuje ispitivanje većega broja uzoraka.

Hudson (**1969**) je uspoređujući dvije indirektne metode, brazilski test i prstenasto ispitivanje, zaključio kako je tako utvrđena vlačna čvrstoća eksperimentalna značajka, a ne značajka materijala.

Mellor i Hawkes (**1971**) mjerili su vlačnu čvrstoću radijalnom kompresijom brazilskoga diska za tri vrste stijena, dvije plastike, stakla i leda, a eksperimentalni rezultati uspoređeni su s teorijskim očekivanjima. Kako bi smanjili naprezanje na mjestu inicijalnih točki, osmislili su izvijenu čeljust za nanošenje naprezanja na uzorak. Svojim istraživanjima istaknuli su kako je brazilski test pogodno ispitivanje za određivanje vrijednosti jednoosne vlačne čvrstoće.

Hudson i suradnici (**1972**) uočili su da se lom brazilskoga diska pojavljuje direktno ispod točaka inicijalnoga opterećenja samo ako se koriste ravne čelične ploče pri ispitivanju sa servoupravljivim ispitnim uređajima. Ovi autori ne preporučuju ni brazilski test niti prstenasto ispitivanje (engl. *ring test*) za određivanje vlačne čvrstoće kao svojstva materijala.

Barla i Innaurato (**1973**) eksperimentalno su i numerički ispitivali prikladnost indirektnih metoda mjerenja vlačne čvrstoće na anizotropnim stijenskim uzorcima. Koristili su se dvama tipovima uzoraka pod različitim orijentacijama duž osi anizotropije. Dokazali su da se eksperimentalni rezultati mogu prikladno objasniti metodom konačnih elemenata.

Wijk (**1978**) je proučavajući primjenu trodimenzionalne raspodjele naprezanja na probleme kod naprezanja i deformacija u ravnini dokazao da se i na uzorcima brazilskoga testa treba upotrebljavati trodimenzionalna korekcija za dvodimenzionalna teorijska rješenja i kod vrlo tankih uzoraka. Te teorijske primjedbe pokazuju da je tumačenje indirektnih ispitivanja vlačne čvrstoće stijenskih materijala teže nego što se prije mislilo.

Tim znanstvenika predvođenih Yanagidanijem (**1978**), koristeći se elektrootpornim trakama za detekciju pukotine, uočio je da inicijalna pukotina ne potječe od točke inicijacije naprezanja, već iz zone vlačnoga naprezanja. Njegovi rezultati imali su izravnu važnost za validaciju brazilskoga testa.

Međunarodno društvo za mehaniku stijena (**ISRM 1978**) usvojilo je standardiziranu metodu brazilskoga testa za indirektno mjerenje vlačne čvrstoće prema izrazu (2). Međutim, postupak direktnoga mjerenja vlačne čvrstoće i dalje ostaje kao metoda za određivanje vlačne čvrstoće stijena.

$$\sigma_{BTS} = 0{,}636 \frac{F}{D \cdot t} \tag{2}$$

gdje je:

σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)
F – sila sloma uzorka (kN)
D – promjer uzorka (mm)

t – debljina uzorka (mm).

Lajtai (**1980**) zaključuje da je vlačna čvrstoća dobivena pomoću ispitivanja indeksa čvrstoće niža od vrijednosti vlačne čvrstoće dobivene brazilskim testom te da je brazilski test preciznije ispitivanje kod različitih smjerova nanošenja sile na uzorak.

Sundaram i Corrales (**1980**) istaknuli su da se pretpostavljanjem istih elastičnih značajki pri vlačnome i tlačnome naprezanju može precijeniti vrijednosti vlačne čvrstoće stijena dobivenih brazilskim testom te su naglasili važnost razmatranja odvojenih elastičnih značajki uzorka pod vlačnim i tlačnim naprezanjem.

Pandey i Singh (**1986**) raspravljaju o karakteristikama deformacija kod vlačnoga naprezanja te otkrivaju da je vlačna čvrstoća dobivena brazilskim testom gotovo dvostruko veća od vrijednosti dobivene direktnom metodom. Na osnovi toga tvrde kako je vlačna čvrstoća zapravo eksperimentalno svojstvo, a ne svojstvo materijala.

Na temelju proučavanja međuovisnosti između BP indeksa (engl. *Block Punch Strength Index*) i indirektne vlačne čvrstoće utvrđene brazilskim testom na uzorcima od breče, kalkarenita, kalklutita, dunita, gnajsa, vapnenaca, mramora, muljnjaka i pješčenjaka utvrđena je jednadžba (3) za izračunavanje indirektne vlačne čvrstoće uz pomoć BP indeksa (**Van der Schrier, 1988**).

$$\sigma_{BTS} = 0{,}4BPI - 0{,}4 \tag{3}$$

gdje je:
σ_{BTS} – indirektna vlačna čvrstoća određena brazilskim testom (MPa)
BPI – BP indeks (MPa).

Newman i Bennett (**1990**) statističkom studijom potvrđuju da odnos dužine i promjera uzorka, kao i prirast naprezanja, imaju znatan utjecaj na indirektnu vlačnu čvrstoću pješčenjaka.

Andreev (**1991a i b**) je proveo svojevrsnu reviziju određivanja vlačne čvrstoće pomoću brazilskoga testa koncentrirajući se na jednadžbu i uvjete kontakta na uzorku. Utvrđuje kako se lom u kontaktnome području uzorka ne događa ako se njegov modul elastičnosti znatno razlikuje od modula elastičnosti naprave za nanošenje naprezanja. Suprotno dotadašnjemu mišljenju zaključuje kako brazilski test daje dobre vrijednosti za materijale koji se krto lome te predlaže jednadžbu (4) prema kojoj bi se računala indirektna vlačna čvrstoća kod takvih materijala.

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \cdot \left(n + \frac{3}{n} \right) \tag{4}$$

gdje je:
σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)
F – sila sloma uzorka (kN)
D – promjer uzorka (mm)
t – debljina uzorka (mm)
n – omjer između tlačne i vlačne čvrstoće.

Razvoj informatičke tehnologije omogućio je zahtjevnija istraživanja te je postalo moguće izrađivanje simulacija procesa loma uz pomoć računalnih programa. Načinjena je dvodimenzionalna numerička simulacija na temelju istraživanja inicijacije i širenja pukotine uz primjenu Mohr-Coulombova kriterija sloma (**Malan et al. 1994**).

Informatičko doba također je olakšalo izračunavanje matematički kompleksnih problema, ali i kompleksnija laboratorijska mjerenja te su Chen i suradnici (**1998**) nakon provedenoga ispitivanja indirektne vlačne čvrstoće anizotropne vrste stijena (4 vrste pješčenjaka) zaključili kako se metode temeljene na pretpostavkama o elastičnoj izotropnosti ne bi smjele koristiti u analizi ispitivanja anizotropnih stijena. Dokazuju da indirektna vlačna čvrstoća anizotropnih stijena nije konstantna, već ovisi o kutu između ravnine anizotropije i osi nanošenja opterećenja na uzorak. Na temelju brazilskoga testa razvijaju metodu mjerenja konstanti elastičnosti koja uključuje mjerenje pomaka pomoću elektrootpornih traka koje se lijepe pod kutom od 45º u odnosu na os nanošenja opterećenja.

Exadaktylos i Kaklis (**2001**) predstavili su eksplicitne izraze naprezanja i deformacija u bilo kojoj točki radijalno opterećenoga anizotropnoga kružnog diska te pokazali da se predložena analitička rješenja mogu učinkovito koristiti u povratnim analizama te kao alat za određivanje elastičnosti i čvrstoće stijena. To je prikazano i u slučaju prije objavljenih eksperimentalnih rezultata na škriljavcima i gnajsevima i u slučaju njihovih ispitivanja na mramoru.

Sulukcu i Ulusay (**2001**) na temelju ispitivanja uzoraka od 23 vrste stijena objavili su jednadžbu (5) za izračun indirektne vlačne čvrstoće preko korigiranoga BP indeksa, a za izračun preko indeksa čvrstoće jednadžbu (6).

$$\sigma_{BTS} = 0{,}86 \cdot BPI_c \tag{5}$$

$$\sigma_{BTS} = 2{,}3 \cdot I_{S(50)} \tag{6}$$

gdje je:

σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)

BPI_c – korigirani BP indeks (MPa)

$I_{S(50)}$ – indeks čvrstoće (MPa).

Lavrov i Vervoort (**2002**) analizirali su utjecaj sile trenja primijenjene na dva suprotna luka raspodjele naprezanja u brazilskome testu. Zaključili su da je distribucija naprezanja unutar uzorka samo neznatno izmijenjena utjecajem trenja na njegovim granicama.

Nakon opažanja akustičkih efekata prilikom ispitivanja prezentirana je analiza Kaiserova efekta degradacije uslijed povećanja odstupanja od glavnoga naprezanja između točaka nanošenja opterećenja kod brazilskoga testa. Korištena je diskontinuirana analiza pomaka za objašnjenje eksperimentalnih rezultata (**Lavrov et al., 2002**).

Nehomogenost materijala ima znatan utjecaj na raspodjelu vlačnih naprezanja uzduž osi nanošenja opterećenja. Za prikaz te spoznaje iskorištena je metoda konačnih elemenata za dvodimenzionalnu analizu geomaterijala. Metodom su modelirane nehomogenosti i mikrostrukture (**Yue et al., 2003**).

Kinesko-švedski istraživači osmislili su metodu koja primjenjuje tanki disk, a kojom bi se jednim ispitivanjem odredili modul elastičnosti, vlačna čvrstoća (7) i lomna žilavost kod stijena koje se krto lome. Kako bi se zajamčila inicijacija pukotina u središtu uzorka, koja se smatra presudnom za valjanost ispitivanja, kut nanošenja opterećenja mora biti veći od 20º (**Wang et al., 2004**).

$$\sigma_{BTS} = \frac{2F}{\pi \cdot D \cdot t} \cdot k_w \tag{7}$$

gdje je:

σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)

F – sila sloma uzorka (kN)

D – promjer uzorka (mm)

t – debljina uzorka (mm)

k_w – koeficijent koji je u bliskoj vezi s kutom nanošenja 2α, za 2α = 20º k = 0,9644; 2α = 30º k = 0,9205.

Kako bi odredili mjesto nastanka pukotine, južnoafrički su znanstvenici provodili ispitivanja na diskovima u kojima su bušili rupe različitoga promjera i mijenjali mjesto rupe na uzorku. Nakon eksperimentiranja i simuliranja loma pretpostavljaju da se pukotina na uzorku brazilskoga testa počinje širiti u blizini jednoga od izvora pritiska na disk (**Van De Steen et al., 2005**).

Talijanski znanstvenici koji su eksperimentirali s raznim alternativnim načinima određivanja vrijednosti vlačne čvrstoće zaključili su da je njezina vrijednost strogo zavisna od odabrane metode ispitivanja. Iznijeli su kritične procjene nekih široko upotrebljavanih laboratorijskih tehnika na temelju eksperimentalnih podataka dobivenih iz literature ili na temelju vlastitih te zaključili kako od laboratorijskih metoda jedino brazilski test daje rezultate slične onima koji se dobivaju direktnim određivanjem vlačne čvrstoće mekih stijena (**Coviello et al., 2005**).

Aydin i Basu (**2006**) uočili su da trošenje uslijed tropske klime oslabljuje mikrostrukture magmatskih stijena pa ponašanje stijene tijekom vlačnoga ispitivanja može biti pokazatelj stanja mikrostrukture i trošenja stijene. Zbog toga su izradili indikator koji se sastojao od 2 cm duge elektrootporne trake smještene na horizontalnu os uzorka. Na taj su način mjerili veličinu koju su nazvali brazilski deformacijski indeks BDI (engl. *Brazilian deformational index*) na osnovi koje se mogu detektirati i minimalne varijacije nastale trošenjem.

Analiza naprezanja bazirana na trodimenzionalnoj metodi konačnih elemenata 3D FEM (engl. *Finite Element Method*) pokazala je važnost veličine i oblika brazilskoga diska. Nametnuo se zaključak kako je jednadžba koja je u prošlosti korištena za indirektno izračunavanje vlačne čvrstoće netočna te da treba biti korigirana prema izrazu (8) u odnosu na odnos debljina/promjer, pogotovo kada se radi o uzorcima povećane debljine (**Yu et al., 2006**).

$$\sigma_{BTS} = \left(0{,}2621 \cdot k_R + 1\right)\frac{2F}{\pi \cdot D \cdot t} \qquad (8)$$

gdje je:
σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)
F – sila sloma uzorka (kN)
D – promjer uzorka (mm)
t – debljina uzorka (mm)
k_R – omjer između debljine i promjera uzorka.

Tim kineskih znanstvenika osmislio je eksperimentalnu metodu za dobivanje vlačnoga modula elastičnosti. U metodi se upotrebljavaju elektootporne trake zalijepljene na uzorke prilikom izvođenja brazilskoga testa, a analitička jednadžba vlačnoga modula elastičnosti prikazana je izrazom (9). Utvrdili su da odnos vlačnoga modula elastičnosti prema tlačnomu modulu elastičnosti iznosi od 60 do 90 % za mramor, pješčenjak i vapnenac (**Ye et al., 2009**).

$$E_{BTS} = A_T \cdot E_S \qquad (9)$$

gdje je:
E_{BTS} – vlačni modul elastičnosti (MPa)
A_T – korekcijski faktor prema izrazu (10)
E_S – elastični modul cijepanja (engl. *splitting elastic modulus*) koji se dobije izrazom (11).

$$A_T = \left(1 - \frac{D}{t} \cdot \arctan\frac{2t}{D}\right) \cdot (1-\nu) + \frac{2D^2 \cdot (1+\nu)}{4t^2 \cdot D^2} \qquad (10)$$

$$E_S = \frac{0{,}5\sigma_t}{\varepsilon_t} \qquad (11)$$

gdje je:
D – promjer uzorka (mm)
t – debljina uzorka (mm)
ν – Poissonov koeficijent
σ_t – najveće naprezanje u testu (MPa)
ε_t – deformacija kod $\sigma_t/2$ koja se određuje iz dijagrama naprezanja i deformacija.

Razmatranje utjecaja inicijalnih pukotina na distribuciju naprezanja dovelo je do modeliranja BEM metodom (engl. *Boundary Element Method*), odnosno simulacije procesa nastanka i širenja pukotina na uzorku koji je izložen indirektnomu vlačnom naprezanju. Analize modela pokazuju da je raspodjela naprezanja samo neznatno pod utjecajem trenja između čeljusti i uzorka. S druge strane, pojava i širenje pukotina koje proizvodi polje naprezanja vrlo je različito od onoga kada je stijenski materijal kontinuiran, homogen, izotropan i elastičan. Smatra se kako analiza deformacije duž promjera uzorka koji je okomit na pravac nanošenja opterećenja omogućava određivanje izravne vlačne čvrstoće tako da se ona detektira kao mjesto gdje je krivulja naprezanja i deformacija okomita na smjer nanošenja naprezanja (**Lanaro et al., 2009**).

Analiza naprezanja metodom 3D FEM, uz pretpostavku da su ispitni materijali kontinuirana, izotropna i homogena elastična tijela, omogućila je izradu modificirane verzije brazilskoga testa. U njemu su postavljena dva specijalna držača razmaka na točkama inicijalnoga opterećenja kako bi se smanjilo koncentriranje naprezanja. Ta je modifikacija napravljena jer se smatralo kako originalna verzija brazilskoga testa znatno podcjenjuje vlačnu čvrstoću ispitnoga materijala. Yu i suradnici (**2009**) predložili su da se indirektna vlačna čvrstoća računa po izrazu (12) za krte stijene.

$$\sigma_{BTS} = \frac{2k_S \cdot F}{\pi \cdot D \cdot t} \tag{12}$$

gdje je:

σ_{BTS} – vlačna čvrstoća određena brazilskim testom (MPa)

F – sila sloma uzorka (kN)

D – promjer uzorka (mm)

t – debljina uzorka (mm)

k_S – koeficijent koji se odnosi na stanje naprezanja u točki inicijacije, a njegova je najbolja vrijednost 1,11.

Tavallali i Vervoort (**2010a,b**) prezentirali su važnost orijentacije slojeva, tj. anizotropije na vlačnu čvrstoću, ali i razvoj pukotina. Uočili su tri različita tipa pukotina kod specifično uslojenoga pješčenjaka s juga Belgije te ih nazvali aktivacija slojeva, središnje frakture i izvansredišnje frakture. Zatim su opisali kako veličina i oblik zrna te mineralni sastav imaju utjecaj na vlačnu čvrstoću utvrđenu brazilskim testom.

Grčki znanstvenici u dva su navrata objavili radove u kojima prikazuju kompletno objašnjenje naprezanja i pomaka u brazilskome disku pod ravnomjerno distribuiranim radijalnim opterećenjem. Međutim, rješenje je izneseno pod pretpostavkom kako je materijal uzorka homogen, izotropan i linearno elastičan. Proučavali su utjecaj ravnomjerno raspodijeljenoga smičnog naprezanja na mjestima nanošenja opterećenja. Uočili su kako će lom prije započeti na rubu kontakta inicijalnih točaka nego u samoj sredini uzorka (**Markides et al., 2010 i 2011**).

Australski znanstvenici predstavili su eksperimentalne rezultate istraživanja odnosa naprezanja i deformacija uzoraka tufa Brisbane koji su bili podvrgavani dvama načinima nanošenja opterećenja. Prvi je sinusoidalno povećanje tlaka, a drugi je prosječno povećavanje razine opterećenja. Otkrili su da je kod takvih uvjeta izvođenja brazilskoga testa indirektno mjerena vlačna čvrstoća reducirana 33 – 37 % (**Erarslan i Williams, 2012**). Na uzorcima tufa Brisbane uspoređivan je utjecaj nanošenja opterećenja pomoću standardnih čeljusti i nanošenja opterećenja na određenome dijelu luka samoga uzorka. Uz eksperimentalna ispitivanja rađene su i numeričke simulacije koje su pokazale kako je najbolja geometrija nanošenja opterećenja $2\alpha = 20° – 30°$ duž luka uzorka (**Erarslan et al., 2012**).

Markides i Kourkoulis (**2012**) bavili su se analizom komponenti naprezanja u uzorcima brazilskoga diska koji su se ispitivali pod četirima različitim tipovima nanošenja opterećenja: nanošenje opterećenja u jednoj točki, jednoliko distribuiran radijalni tlak, sinusoidalno nanošenje tlaka, parabolično nanošenje tlaka. Parabolično nanošenje ocijenjeno je kao najbolje, a nedostatak je njihove analize u tome što je izrađena pod pretpostavkom linearne elastičnosti i uz ignoriranje utjecaja smicanja.

Indijski znanstvenici u nastojanju poboljšanja mogućnosti BP testa objavili su jednadžbu (13) za proračun indirektne vlačne čvrstoće za granit, škriljavac i pješčenjak. Po njihovim istraživanjima međuovisnost indirektne vlačne čvrstoće utvrđene brazilskim testom veća je s korigiranim BP indeksom nego s indeksom čvrstoće koji je utvrđen opterećenjem u točki (**Mishra i Basu, 2012**).

$$\sigma_{BTS} = 0{,}35 \cdot BPI_c + 3{,}69 \tag{13}$$

gdje je:

σ_{BTS} – indirektna vlačna čvrstoća određena brazilskim testom (MPa)

BPI_c – korigirani BP indeks (MPa).

Kazareni (**2013**) je predstavio model temeljen na diskontinuumu kojim je simulirao vlačni i tlačni slom pješčenjaka. Model vjernije reproducira stijenski materijal koji je gust skup nepravilnih i izobličenih čestica koje imaju interakciju na svojim granicama. Zaključuje kako se takav način modeliranja može koristiti za opisivanje odnosa između mikrostrukturnih i makrosvojstava materijala.

Li i Wong (**2013**) iznijeli su pregled dosadašnjih istraživanja vezanih uz brazilski test te proveli numeričku analizu izrađujući elastični model u 3D FLAC programu. Koncentrirajući se na točku inicijacije pukotine, zaključuju kako se inicijacijska točka može nalaziti u blizini točaka nanošenja opterećenja u trenutku kada vlačna deformacija zadovoljava kritični kriterij deformacije, a također može biti smještena u središtu kada vlačno naprezanje zadovoljava kriterij maksimalne vlačne čvrstoće.

Tehnika snimanja pomoću brzih kamera primijenjena je kod ispitivanja indirektne vlačne čvrstoće pod statičkim i dinamičkim opterećenjem granitnih uzoraka u svrhu istraživanja za građevine u podzemlju. Primijećena su četiri načina loma uzoraka: dijametralno vlačni lom, središnji lom s malim klinovima kod točaka nanošenja opterećenja, središnji lom sa zdrobljenom zonom i lom s inicijacijom iz smično oštećenih rubnih zona. Na osnovi toga autori preporučuju da se kod analize ispravnosti loma uzoraka koristi kamera velike brzine snimanja jer uobičajena optička analiza može zavarati (**Zhou et al., 2014**).

Turski su znanstvenici napravili evaluaciju indirektne vlačne čvrstoće kod ispitivanja s različitim vrstama čeljusti za nanošenje tlačnoga opterećenja na uzorak. Njihov rad pokazuje kako različiti materijali različito reagiraju na nanošenje opterećenja pa se za sve vrste materijala ne može primjenjivati isti tip čeljusti (**Komurlu i Kesimal, 2015**). Njihovu radu može se prigovoriti malen broj ispitivanja po pojedinome materijalu i vrsti čeljusti koji nekada iznosi i 4 komada, što je svakako nedovoljno.

Nedavno je tim kineskih znanstvenika iznio prijedlog promjene jednadžbe izračuna indirektne vlačne čvrstoće. Pri tome im je Poissonov koeficijent bio najvažniji čimbenik, zatim kut nanošenja opterećenja i omjer debljine i polumjera. Otkrili su da povećanje Poissonova koeficijenta te manji kut nanošenja smanjuju pojavu središnje inicijacije pukotine. Prema Griffithovu kriteriju modificirali su jednadžbu u skladu s preporučenim područjem vrijednosti. Jednadžba (14) usklađena je s prijašnjim studijama, brojčano i eksperimentalno (**Lin et al., 2015**).

$$\sigma_{BTS} = -\left(1{,}027 + 0{,}108\nu - 0{,}014\alpha\right) \cdot \frac{F}{\pi \cdot r \cdot t} \tag{14}$$

gdje je:

σ_{BTS} – indirektna vlačna čvrstoća određena brazilskim testom (MPa)

ν – Poissonov koeficijent

α – polovina kuta nanošenja opterećenja

F – sila sloma uzorka (kN)

r – polumjer diska (mm)

t – debljina diska (mm).

Prema dostupnoj literaturi ispitivanja vlačne čvrstoće brazilskim testom na materijalima s područja Hrvatske vezana su uz razna istraživanja provedena u svrhu izvođenja geotehničkih građevina, pogotovo cestovne infrastrukture (**Šestanović et al., 1993**, **Pollak, 2002**) te uz ispitivanja u svrhu dimenzioniranja podzemnih prostorija prilikom podzemne eksploatacije arhitektonsko-građevnoga kamena (**Hrženjak et al., 2008**). Indirektna vlačna čvrstoća ispitivana je kod djelovanja sile u smjeru okomitome na slojne plohe i u slučaju djelovanja sile u smjeru paralelnome sa slojnim plohama za krovinske slojeve „A”, „E” i „F” ležišta arhitektonsko-građevnoga kamena „Korenići” u Istri (**Dobrilović et al., 2010**). Također istraživan je utjecaj saturacije na indirektnu vlačnu čvrstoću gipsa (**Macenić, 2011**) i vapnenca (**Čajić, 2015**).

Važno je naglasiti da postoje razlike između rezultata direktnoga i indirektnoga mjerenja vlačne čvrstoće pomoću brazilskoga testa, a to se može vidjeti u **tablici 1**, gdje su prikupljeni podatci iz relevantne literature te izračunan odnos $\sigma_{BTS}/\sigma_{UTS}$. Zanimljivo je što se kod nekih materijala, npr. vapnenca, parcijalno pokazuje obrnuti trend odnosa $\sigma_{BTS}/\sigma_{UTS}$ od onoga kada su podatci objedinjeni. Vapnenci tipa Indijana i Saraburi pokazuju kako brazilski test precjenjuje njihovu čvrstoću, dok vapnenci skupno pokazuju da im taj test umanjuje čvrstoću.

Tablica 1: Odnos vlačne čvrstoće određene direktnim postupkom i indirektne vlačne čvrstoće određene pomoću brazilskoga testa

Tip stijene	σ_{UTS}	σ_{BTS}	$\sigma_{BTS}/\sigma_{UTS}$	Izvor
trahit Bowral	13,72	12,00	0,87	Jaeger (1967)
trahit	13,7	7,7	0,56	Perras i Diederichs (2014)
sijenit Vitosha	20,50	21,05	1,03	Andreev (1991a)
granit Barre	13,45	14,34	1,07	Mellor i Hawkes (1971)
granit	6,3	10,3	1,63	Perras i Diederichs (2014)
mramor Carrara	6,90	8,72	1,27	Jaeger (1967)
mramor Ufalei	5,90 ± 2,66	6,90 ± 1,24	1,17	Efimov (2009)
mramor Saraburi	6,33 ± 0,62	8,02 ± 0,25	1,27	Fuenkajorn i Klanphumeesri (2011)
mramor	7,5	10,1	1,35	Perras i Diederichs (2014)
gnajs	8,2	9,8	1,2	Perras i Diederichs (2014)
kvarcit	16,3	13,0	0,8	Perras i Diederichs (2014)
škriljavac	13,3	11,8	0,89	Perras i Diederichs (2014)
šejl	5,6	5,9	1,05	Perras i Diederichs (2014)
sivi gips	1,75	1,99	1,14	Andreev (1991a)
bijeli gips	1,42	1,29	0,91	Andreev (1991a)
pješčenjak Godsford	3,59	3,72	1,04	Jaeger (1967)
pješčenjak Phu Phan	6,49 ± 0,22	10,68 ± 0,70	1,65	Fuenkajorn i Klanphumeesri (2011)
pješčenjak	5,1	9,5	1,86	Perras i Diederichs (2014)
gravina kalkarenit	0,69 ± 0,03	0,64 ± 0,10	0,93	Coviello et al. (2005)
vapnenac Indiana	5,86	6,21	1,06	Mellor i Hawkes (1971)
vapnenac Saraburi	9,31 ± 0,65	10,90 ± 0,19	1,17	Fuenkajorn i Klanphumeesri (2011)
vapnenac	7,1	6,0	0,85	Perras i Diederichs (2014)
dolomit	5,7	8	1,4	Perras i Diederichs (2014)

σ_{UTS} – vlačna čvrstoća određena direktnim postupkom; σ_{BTS} – vlačna čvrstoća određena brazilskim testom

2. Procjenjivanje vlačne čvrstoće uz pomoć drugih značajki

Prema Hoeku (**1966**) uobičajeno se smatra kako vlačna čvrstoća iznosi jednu desetinu u odnosu na tlačnu čvrstoću te se može računati izrazom (15).

$$\sigma_{UTS} = -\frac{\sigma_{UCS}}{10} \tag{15}$$

gdje je:
σ_{UTS} – direktna vlačna čvrstoća (MPa)
σ_{UCS} – jednoosna tlačna čvrstoća (MPa).

Zhang (**2005**) predlaže da se tlačna čvrstoća za pojedini stijenski materijal može izračunati jednadžbom (16), a za proračun vlačne čvrstoće preko indeksa čvrstoće jednadžbom (17).

$$\sigma_{UTS} = -k_m \cdot \sigma_{UCS} \tag{16}$$

$$\sigma_{UTS} = -1{,}5 \cdot I_{S(50)} \tag{17}$$

gdje je:
σ_{UTS} – direktna vlačna čvrstoća (MPa)
σ_{UCS} – jednoosna tlačna čvrstoća (MPa)
k_m – koeficijent koji ima vrijednost od 0,03 do 0,24 ovisno o vrsti stijene
$I_{S(50)}$ – indeks čvrstoće (MPa).

Perras i Diederichs (**2014**) nakon pregleda relevantne literature zaključili su kako je najveća pogrješka kod procjene preko jednoosne tlačne čvrstoće, a manja ako se za procjenu primjenuje Hoek-Brownova konstanta „m_i" prema izrazu (18).

$$\sigma_{UTS} = -\frac{\sigma_{UCS}}{m_i} \tag{18}$$

gdje je:
σ_{UTS} – direktna vlačna čvrstoća (MPa)
σ_{UCS} – jednoosna tlačna čvrstoća (MPa)
m_i – Hoek-Brownova konstanta materijala.

Uporaba mjerene veličine pod nazivom inicijacija pukotine (skr. CI, engl. *crack initiation*) za procjenu direktne vlačne čvrstoće prema izrazu (19) daje bolje rezultate od korelacije preko jednoosne tlačne čvrstoće, međutim takva procjena ovisna je i o vrsti stijene pa izraz (19) treba u budućnosti modificirati prema osobinama materijala (**Perras and Diederichs, 2014**).

$$\sigma_{UTS} = -\frac{CI}{k_\beta} \tag{19}$$

gdje je:
σ_{UTS} – direktna vlačna čvrstoća (MPa)
CI – inicijacija pukotine (MPa)
k_β – koeficijent koji iznosi 8 po originalnome Griffithovu kriteriju ili 12 nakon modifikacije originalnoga Griffithova kriterija.

Švicarski su znanstvenici na osnovi pregleda literature iz područja određivanja vlačne čvrstoće generalno zaključili kako je direktnu vlačnu čvrstoću teško procijeniti na osnovi drugih laboratorijskih ispitivanja. Zaključuju kako je procjena direktne čvrstoće preko indirektne vlačne čvrstoće određene brazilskim testom ovisna o vrsti stijene te preporučuju da se obavlja prema izrazu (20) kako bi se poboljšala procjena (**Perras and Diederichs, 2014**).

$$\sigma_{UTS} = \sigma_{BTS} \cdot k_T \tag{20}$$

gdje je:
σ_{UTS} – direktna vlačna čvrstoća (MPa)
σ_{BTS} – indirektna vlačna čvrstoća određena brazilskim testom (MPa)
k_T – korekcijski faktor koji iznosi 0,9 za metamorfne, 0,8 za magmatske i 0,7 za sedimentne stijene.

3. Utjecaj saturacije uzoraka na njihovu vlačnu čvrstoću

Što se tiče utjecaja saturacije na vlačnu čvrstoću, stariji radovi samo se uopćeno bave tom problematikom. Dube i Singh (**1972**) istražuju utjecaj humidne klime na indirektnu vlačnu čvrstoću pješčenjaka koju su određivali brazilskim testom. Otkriveno je kako su šupljikavi pješčenjaci te oni koji su u svojemu sastavu imali minerale glina najviše skloni smanjenju vlačne čvrstoće.

Opsežnije istraživanje provodi **Vutukuri** (**1974**) koji se bavio alternativnim metodama za određivanje vlačne čvrstoće. Koristio se prstenastim ispitivanjem za određivanje vlačne čvrstoće uzoraka vapnenca te je ispitivao ovisnost utjecaja raznih vrsta tekućina na vrijednosti vlačne čvrstoće vapnenaca. Saturaciju u trajanju od 20 sati provodio je vodom, glicerinom, etanolom, nitrobenzenom i s nekoliko tekućina organskoga sastava. Otkrio je da se kod porasta dielektrične konstante i površinske napetosti tekućine smanjuje vlačna čvrstoća vapnenaca.

Ojo i Brook (**1990**) ispitivali su jednoosnu tlačnu čvrstoću i direktnu vlačnu čvrstoću pješčenjaka koji je bio različitoga stupnja saturacije. Otkrivaju kako se obje čvrstoće smanjuju s povećanjem stupnja saturacije, a odnos jednoosne tlačne čvrstoće i direktne vlačne čvrstoće veći je u saturiranome (zasićenome) nego u suhome stanju. Tvrde da je smanjenje čvrstoće uslijed utjecaja saturacije više izraženo kod direktne vlačne čvrstoće nego kod jednoosne tlačne čvrstoće.

Od novijih radova valja istaknuti rad kineskih znanstvenika koji su istraživali učinak zasićenosti uzoraka vodom na indirektnu vlačnu čvrstoću gnajsa, mramora i pješčenjaka. Rezultati istraživanja pokazali su da sve navedene stijene imaju nižu vlačnu čvrstoću zasićene negoli suhe. Ispitivanja su obavljali brazilskim testom i prstenastim ispitivanjem te zaključili kako prstenasto ispitivanje pokazuje male razlike čvrstoće suhih i saturiranih uzoraka (**You et al., 2011**).

Singapurski znanstvenici proučavali su utjecaj saturacije na indirektnu vlačnu čvrstoću umjetnoga gipsa te su se pri tome koristili brzim kamerama. Rezultati pokazuju pad čvrstoće na pola vrijednosti čvrstoće u suhome stanju, nakon samo jednoga tjedna saturacije. Snimke brzim kamerama pokazuju kako se inicijalna pukotina kod većine uzoraka stvara u središtu, a postoji razlika između načina loma suhih i saturiranih uzoraka. Suhi uzorci pucaju nakon samo jedne inicijacije, a pukotina im se vrlo brzo širi, dok saturirani imaju više inicijalnih pukotina i mirniji razvoj primarne vlačne pukotine (**Wong and Jong, 2013**).

4. Zaključak

Velik broj radova koji se bave problematikom vezanom uz brazilski test posljedica je njegove naravi. S jedne strane, jednostavna obrada uzoraka omogućava brzu eksperimentalnu provjeru numeričkih analiza i raznih simulacija. S druge strane, njegova osjetljivost zahtijeva pažljivo objašnjenje ponašanja materijala prilikom ispitivanja i pronalaženje rješenja za otklanjanje nepravilnosti.

Novija istraživanja pokazuju kako se pri proučavanju brazilskoga testa treba više posvetiti razlikama koje nastaju zbog različitih svojstava pojedinih vrsta ispitivanih materijala jer je pitanje anizotropije uglavnom riješeno. U bližoj budućnosti ne očekuje se standardizacija postupaka koji primjenjuju skuplju i kompliciraniju opremu, čime se može znatno poboljšati samo ispitivanje. Daljnja istraživanja indirektne vlačne čvrstoće treba usmjeriti na istraživanje utjecaja saturacije na različite vrste stijenskoga materijala jer bi to bilo od praktične koristi u inženjerstvu.

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