WATER SATURATION INDUCED CHANGES IN THE INDIRECT (BRAZILIAN) TENSILE STRENGTH AND THE FAILURE MODE OF SOME IGNEOUS ROCK MATERIALS

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ABSTRACT

The present study concentrates on water induced strength reduction and variation of the failure mode in indirect (Brazilian) tension tests of several igneous rock materials under three moisture cases of oven-dry, air-dry and fully saturated states. In this respect, two andesite and three tuff materials which contain no visible flaws were subjected to indirect tensile strength tests using the Brazilian disc method. Once the tension tests were carried out, photographs of the broken samples were taken to investigate the changes in the failure mode. As a result, it was found that tensile strengths of the samples were highly reduced with the presence of the water and the natural humidity. Additionally, it has been deduced that the failure mode of the samples mainly shifts to central fracturing with the presence of natural moisture and saturation. Although the central crack is the ideal type for the theory of Brazilian tensile strength determination, indefinite contact properties like contact angle and frictions are some notable issues to make only considering failure shapes for the validity of the test results misleading.

Keywords: Failure mode; Igneous Rocks, Strength reduction; Tensile strength

1   INTRODUCTION

Mechanical properties of rocks are sensitive to the testing and environmental conditions, such as loading rate, platen type, moisture content, etc. Moisture or water presence in rocks is one of the main factors controlling the strength and failure mode of the rocks, and the effect of the water saturation on the mechanical properties of rocks have been investigated for a long time since the 1940s [1].

While most of the studies concentrated on the weakening effect of water on the uniaxial compressive strength, lesser amount of research focused on the strength reduction in tension tests. Broch (1974) is known to be first to investigate the strength reduction in tension tests [2]. On the other hand, even though numerous studies investigated the effect of saturation on the strength reduction, a limited number of the studies concentrated on the variation of the failure type or mode, especially in tension tests. Wong and Jong (2014) handled this subject using a high-speed camera to capture the failure type variations in tension tests for a gypsum specimen [3]. Furthermore, most of the studies on the saturation effect dealt with the sedimentary rocks, especially with the sandstones. There is a paucity of the experimental data for tensile strength and failure mode of igneous rocks.

There are different direct and indirect testing methods for determination of tensile strength values of rock materials. Because the conventional (standard) direct tensile strength (DTS) test method has an important disadvantage of possible glue part failure which is more widely seen for high strength rock materials, researchers have proposed alternative test methods for determination of the tensile strength value. As an example, use of the dog-bone (or dumbbell) shaped rock specimens for effective holding is among various DTS testing methods. However, the dog-bone shaped specimens are not widely used as a result of impractical preparation details [4-7].

In addition to DTS tests, various indirect tensile strength (ITS) test methods were also developed. Because of its practicality, the Brazilian test (or splitting tensile strength test) is the most popular one in ITS tests. Although the Brazilian test is applied worldwide, its deficiencies have been discussed as an important issue of the rock testing area [8-11]. Because the Brazilian test discs fail under biaxial stress distribution condition, the method is not usable to evaluate the uniaxial tensile strength values [12-15]. The Brazilian test has another problem of having indefinite contact properties, e.g. contact angle and frictions, which significantly change the stress distribution in

rock discs depending on deformation characteristics of specimens. ITS values obtained from the Brazilian test are not only dependent on the strength of the disc specimen material, but also dependent on its deformability properties [16-18]. Evaluation of the ITS values of rock material specimens under the diametric compression is disadvantageous also because of the possibility of failure initiation in the compression zone beneath the contact points of the loading jaw [19-21].

This paper aimed to investigate another issue of water content effect on weakening and failure mode changes of disc specimens loaded under the standard Brazilian test jaws. Homogenous rock samples with no visible flaws were selected and indirect (Brazilian) tensile strength tests were applied on these samples with three moisture cases of oven-dry, air-dry and fully saturated. Additionally, changes in failure modes and measured strength value results obtained from various water presence cases were discussed with the relevant literature.

2 EXPERIMENTAL STUDIES

Homogenous rock samples which contain no visible flaws were used in the experimental campaign. Two different andesite and three different tuff rock materials mainly obtained from the quarries located near Trabzon were used during the study. Block samples were cored with a NX-type diamond core bit and the samples were sawn carefully to produce high quality and representative samples. Sample preparation stage was carried out according to the recommendations of ISRM (2007) and thickness to diameter ratio of the samples were fixed to 0.5. Overall, 30 samples were prepared for each rock type, which means a total of 150 samples [22]. Three moisture cases were applied in the study which are oven-dry (case 1), saturated (case 2) and air-dry (case 3). Oven-dry samples were held in an oven at 105 C° for 24 hours until they lost their moisture content and stored in a desiccator until the execution of the tension tests. Saturated samples were simmered in water for at least 48 hours to maintain a fully saturated condition and once they have reached a fully saturated state, they were subjected to the Brazilian tensile strength test. Finally, air-dry samples were, firstly, dried in an oven and then exposed to the atmospheric humidity in an open laboratory environment for three months.

Since it is very difficult to obtain the tensile strength of the rock materials directly, in general, indirect methods are preferred in the literature and the Brazilian disc method is the most widely used indirect method for tensile strength determination of rock materials. The Brazilian test involves the diametrical loading of disc shaped specimens until they fail as a result of creating a tensile stress zone. After the test, the failure load was recorded, and the tensile strength of the rock is computed using Eq.1 [22].

$$\sigma_t = \frac{2P}{\pi Dt} \tag{1}$$

where σ_t is the tensile strength (MPa), P is the failure load (N), D is the diameter of the specimen (mm), and t is the thickness of the disc specimen (mm). The tensile strength of the rocks was determined using the Brazilian disc method with the standard jaw seen in Figure 1 according to the recommendations of ISRM [22]. Loading rate was applied as 0.2 kN/s and ten replications were made for each rock sample and moisture case. Tensile strength for three moisture cases were recorded as σ_{to}, σ_{ts}, σ_{ta} for oven-dry samples, saturated samples and air-dry samples, respectively. At total, 150 tests were accomplished.

Since the porosity of rock materials is determinative for their saturation capacity, apparent porosities of the rock samples were evaluated. Effective or apparent porosity (n), which is the connected voids within the samples, was calculated by fully saturating the samples and determining the volume of water absorbed by the rock.
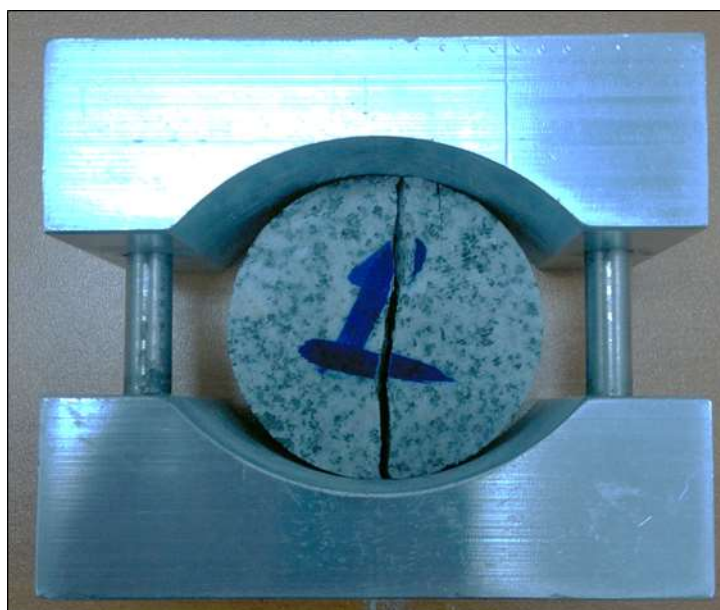
Figure 1. The standard jaw used in the indirect tension test

3   RESULTS AND DISCUSSIONS

Results of the tension tests are presented in Table 1. It is seen from the table that the measured strength values of the rocks highly decreased once the moisture or water meets with the rock samples. The weakening effect is the most pronounced in the tuff 3 sample with a reduction up to 57.6 % with the change of the oven-dry state to saturated state. The reduction values for other samples were observed as 42.4 %, 38.8 %, 23.7 % and 14.9 % for tuff 1, andesite 2, tuff 2 and andesite 1, respectively. Indirect tensile strength of the tuffs and andesites notably changed with variations in the moisture content as evidenced in previous studies [23-25]. Even though the present literature includes many studies about the weakening effect of water on compressive strength, fewer studies focused on sensitivity of the tensile strength, especially for tuffs and andesites.

Table 1. Mean results of the indirect (Brazilian) tensile strength tests and apparent porosities

Rock Sample	σ_{to} (MPa)	σ_{ta} (MPa)	σ_{ts} (MPa)	n (%)
Andesite 1	5.52 ± 1.31	4.96 ± 1.18	4.70 ± 0.78	14.19 ± 2.67
Andesite 2	10.14 ± 1.18	7.73 ± 0.87	6.20 ± 1.22	5.38 ± 0.86
Tuff 1	8.18 ± 0.36	7.68 ± 0.79	4.71 ± 0.93	11.08 ± 1.40
Tuff 2	8.94 ± 0.52	8.27 ± 0.78	6.80 ± 0.73	13.03 ± 2.18
Tuff 3	7.29 ± 0.64	5.57 ± 0.34	3.09 ± 0.47	21.00 ± 0.54

It is worth noting here that the natural moisture content which can be gained by the sample in an open laboratory environment has a significant effect on the mechanical strength. A little amount of moisture of air-dry samples can lead to a high amount of strength reduction such as 23.8 %, 23.6 %, 10.1 %, 7.2 % and 6.1 % for andesite 2, tuff 3, andesite 1, tuff 2 and tuff 1, respectively. It is important to note here that the highest strength reduction was seen in tuff 3 with full saturation, whereas andesite 2 demonstrated the highest strength reduction in air-dry condition.

A complex mechanism and couplings of different mechanisms are involved in the strength reduction due to the water saturation which can be listed as follows: (1) fracture energy reduction; (2) capillary tension decrease; (3) pore pressure increase; (4) frictional reduction; and (5) chemical and corrosive deterioration [26]. It can be stated that coupling of these causes might be accused of the strength reduction.

Basu et al. (2013) investigated the failure modes in the Brazilian tests and used a similar terminology with Tavallali and Vervoort (2010), and defined four main modes of failure shown in Figure 2, which are central (C), non-central (NC), central + layer activation (CL), central multiple (CM). The non-central modes are generally characterized with a curved failure path starting from the contact points of the loading platens. Central and multiple central failure modes are generally stated to be result of a high strain energy stored in the radially loaded disc

sample and results in a high tensile stress. Central and layer activation mode might be seen in the samples which contain anisotropy and layering [27, 28].

Broken samples were photographed after tension tests to investigate the failure modes and the photos of the broken samples are given in Figures 3-5. Additionally, a summary on the number of failed samples by means of failure type is given in Table 2. As it is clear from the table, there was no central and layer activation (CL) type failure in this rock sample group, which can be attributed to the anisotropy, and the rock samples in this study had no anisotropy. Except for tuff 3, all samples showed a tendency to change their failure mode from others to central fracture (C) by the presence of moisture and water. This situation may be stated as the most significant outcome of this study.
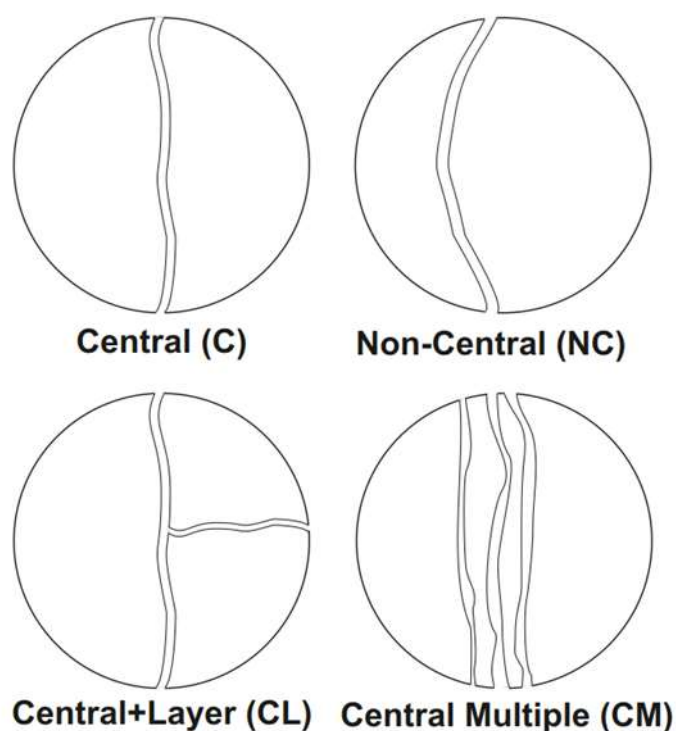

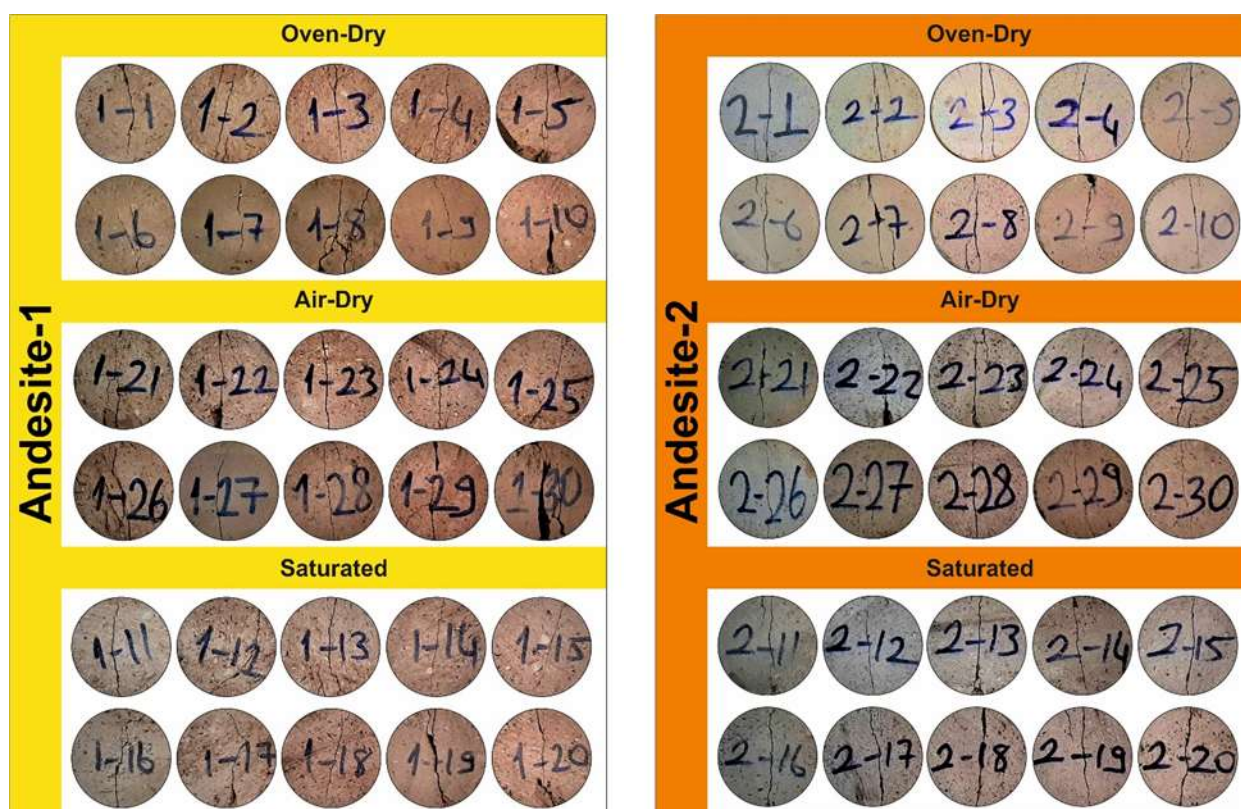**Figure 2. Failure modes in the Brazilian disc test [27, 28]**

Figure 3. Failure photos of Andesite samples in the Brazilian (indirect) tension tests
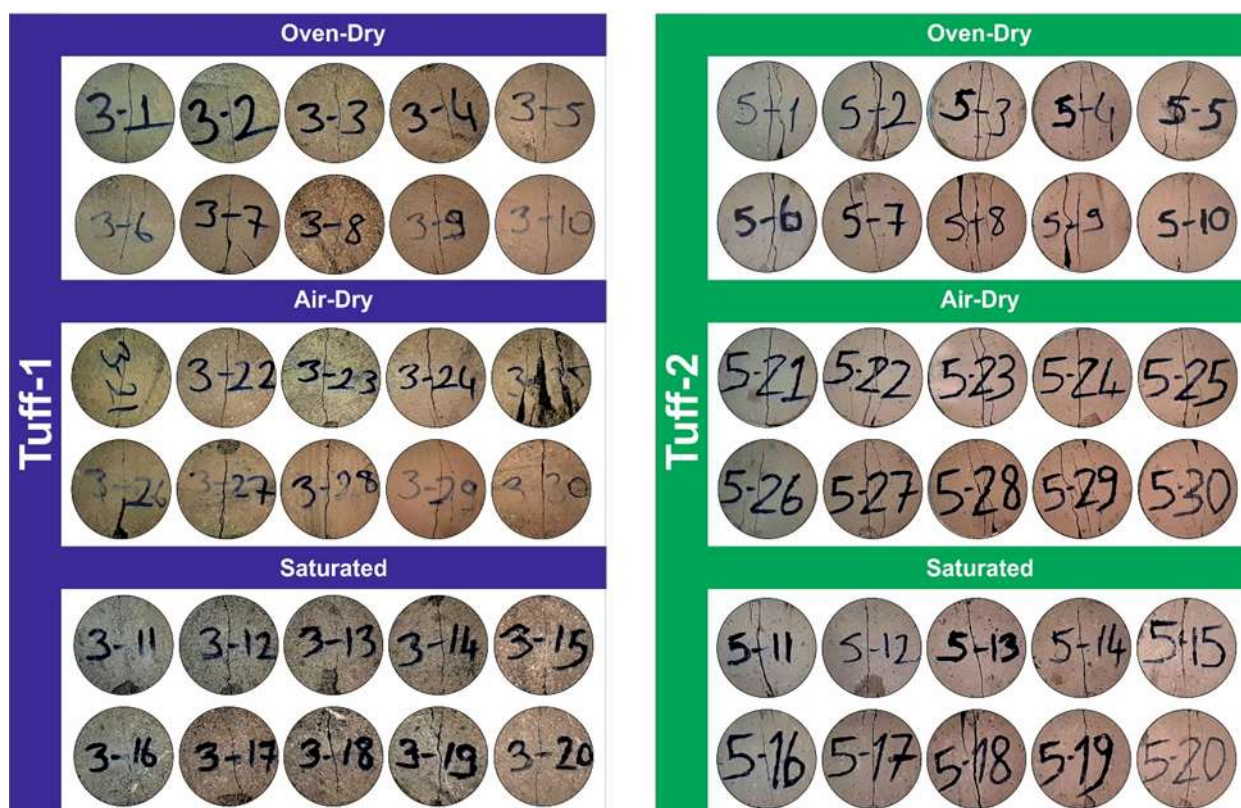

Figure 4. Failure photos of tuff-1 and tuff-2 samples in the Brazilian (indirect) tension tests

Figure 5. Failure photos of the tuff-3 samples in the Brazilian (indirect) tension tests

Table 2. Failure modes of the samples for different moisture contents

	Oven-dry				Air-dry				Saturated			
Failure Mode	**C**	**NC**	**CL**	**CM**	**C**	**NC**	**CL**	**CM**	**C**	**NC**	**CL**	**CM**
Andesite 1	5	3		2	8	2			6	4		
Andesite 2	8			2	9	1			10			
Tuff 1	9	1			9			1	10			
Tuff 2	3	1		6	4			6	9			1
Tuff 3	7	2		1	7	1		2	5	2		3

The standard Brazilian jaw is concave and has an arch diameter of 8.1 cm. When loading initiates, the applied force can be considered linear for standard jaws. However, a significant contact area develops beneath the jaws once the disc significantly deforms [29]. The contact area under the standard jaw varies in accordance with the disc material, jaw material and load level. In the standard Brazilian test (splitting indirect tensile strength test), discs fail under biaxial stress conditions, including radial compressive stress along the vertical diameter and tangential tensile stress along the horizontal diameter of the disc [30, 31]. The tangential tensile stress and compressive radial stress maximize at the centre of the disc; thus, the crack initiation is expected to occur at the centre of the disc. The maximum tensile stress at the centre can be calculated using Eq. (1) derived from Muskhelishvili's equations suggested to estimate stress distribution in discs diametrically compressed under a line load [32]. Based on the theory, standard formulation given in Eq. 1 is not suggested to be used in case of having contact angles higher than 11°, because the line load condition is not valid anymore. Especially for testing soft rocks, contact angle can increase over 30°, which is not exactly suitable for using standard formulation given in Eq. 1 [33]. Therefore, results obtained from the use of standard jaw with no definite contact angle condition are assessed to be misleading. There is a mathematical approach to calculate stress distribution in discs with definite contact angles, reported by Hondros (1959) [34]. However, the Hondros' equations are not applicable with discs loaded under standard jaw because of unknown contact angles.

With an increase in the water content, the contact angle and deformability of rock materials increase. Erarslan and Williams (2012) observed similar results with those obtained from this study that central failure

cracks occurred under high contact angles in tests of another tuff material, the Brisbane tuff [35]. The researchers reported that the contact angle affects the fracture toughness of the disc samples such that toughness increases with an increase in loading angle. The central multiple (CM) cracks sometimes occur following the central (C) crack because loading with high contact angles can prevent the migration in two centrally divided parts under the increase of load. The test should be stopped after seeing the central crack to prevent measuring excessive results.

According to both Muskhelishvili and Hondros' equations, maximum tensile stress occurs at the centre of the disc. Therefore, ideal cracking type for a valid tensile strength value calculation is the central (C) type. Although central failure shape is most likely to be seen in the tests of saturated rock materials, the test cannot be assessed as ideal by only considering the failure shape. Since the formulation can be misleading as a result of having high but unknown contact angles of the saturated disc specimens.

The effect of friction between platens and discs is another important topic in terms of fracturing behaviours of the disc specimens [36, 37]. Influence of frictions cannot be neglected for non-uniformly applied radial stresses at the contact. Markides et al. (2012) noted that radial stresses on the disc contact area are non-uniform in the Brazilian test applications [38]. With a change in the water content, friction stresses are expected to notably vary. However, the friction effect is neglected in the standard formulation given in Eq. 1. Markides et al. (2012; 2011), Kourkoulis and Markides (2012) and Kourkoulis et al. (2013) have reported detailed analysis on contact friction and its effect on stress distribution and deformations of discs under loading of uniformly and non-uniformly distributed stresses [38-41].

In the standard Brazilian test, failure initiates at the centre of the discs under biaxial stress conditions, including compressive radial stress (s_r) along the vertical diameter and tangential stress (s_q) along the horizontal diameter of the disc. Therefore, it should be noted herein that stress distribution in discs cannot be compared with the uniaxial tension. The effect of radial stress on central tensile cracking increases along with an increase in the internal friction angle, which is also not considered in the standard formulation of indirect tensile strength determination [42, 43].

4   CONCLUSIONS

This paper summarizes the results of a series of indirect tension tests under different moisture states for different types of igneous natural stones, such as tuffs and andesites. Indirect tensile strength tests were applied on the disc shaped samples in three different moisture states, i.e. oven-dry, air-dry, and saturated. It has been found that the failure load values of the tuffs and andesites were highly reduced with the presence of natural moisture and water. Additionally, changes in the failure mode were investigated using the post-failure photos. As a summary, the first crack initiation according to the theory should take place centrally and cracking should propagate under the control of the induced tensile stresses along the vertical diameter. Therefore, the central (C) type cracking is the ideal one within various shapes. Nearly 30 % of specimens were failed with an invalid crack shapes for using the strength calculation theory. As a general trend, it has been found that the samples changed the failure mode to central fracture with fully water saturation, except for a tuff type (tuff 3). Although crack shapes generally seem to be more ideal for the saturated specimens, non-usable formulation for high contact angles is doubtful. The increase in the contact angle with increasing deformability makes considering only crack shapes misleading to assess the test accuracy. The Brazilian test has various disadvantages despite of being the most widely used indirect tensile strength test method, worldwide. This study aimed to deal with some problems of determination indirect tensile strength values by the Brazilian method. The results of this study are promising for further studies on the assessment of the usability of the method.

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