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Dog bone shaped specimen testing method to evaluate tensile strength of rock materials

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Abstract. To eliminate the holding and gluing problems making the direct tensile strength test hard to be applied, a new method of testing specimens prepared using lathe machine to make the dog bone shape is assessed whether it could be applied to determine accurate direct tensile strength values of rock materials. A series of numerical modelling analyses was performed using finite element method to investigate the effect of different specimen and steel holder geometries. In addition to numerical modelling study, a series of direct tensile strength tests was performed on three different groups of rock materials and a rock-like cemented material to compare the results with those obtained from the finite element analyses. A proper physical property of the lathed specimens was suggested and ideal failure of the dog bone shaped specimens was determined according to the results obtained from this study.

Keywords: tensile strength; rock testing; direct tensile strength test for rock materials; static loading

1. Introduction

Because the conventional rock tensile strength test is not practical to apply, many different kinds of indirect tensile strength (ITS) methods were suggested by different researchers. Splitting tensile strength (Brazilian) test is the most famous ITS determination method because of its practicality and ability to be carried out using conventional press equipments. Specimen preparation impracticality can be accepted to make some other ITS testing methods be not widely applied. One of the reasons for popularity of the Brazilian test is easy specimen preparation to test under basic loading devices. Although the Brazilian test is applied worldwide, its deficiencies cannot be ignored and have been an important issue to investigate by the community on rock testing (Li and Wong 2013, Komurlu *et al*. 2016a, Briševac *et al*. 2015, Markides and Kourkoulis 2013).

Because the Brazilian discs fail under biaxial stress conditions, including tangential stress (σ_θ) long the horizontal diameter of the disc and compressive radial stress (σ_r) along the vertical diameter of the disc, the Brazilian test has an important problem and cannot be used to determine a tensile strength value to be used instead of uniaxial tensile strength of rock materials (Chen and

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Stimpson 1993, Fairhurst 1964, Krishnayya and Eisenstein 1974, Erarslan and Williams 2012). To be a standard test, the Brazilian test has additional problems resulting from indefinite contact conditions that significantly change the stress distribution in discs with a change in the disc material. Because important factors for stress distribution in the disc specimen such as contact angle and friction conditions vary depending on the rock deformation characteristics, ITS values obtained with the Brazilian test are not only dependent on the strength of the disc specimen material (Komurlu and Kesimal 2015, Markides and Kourkoulis 2016, Kourkoulis *et al*. 2013).

The tensile strengths of brittle materials like rock and concrete are generally much smaller than their compressive strengths. As the ratio between compressive and tensile strengths decreases, the determination of the ITS of materials under diametral compressive loading appears to be a disadvantage due to possibility of crack initiation in the compression zone beneath the contact points (Fairhurst 1964, Erarslan *et al*. 2012, Mikl-Resch *et al*. 2015).

Some other ITS determination methods are three or four point flexural strength test which have been being applied for long years since before the invention of the Brazilian test by Carneiro (1943), the ring test suggested by Hobbs (1965), Luong's test suggested by Luong (1986), confined tensile strength test method of Hoek and Brown (1980). As the direct tensile strength (DTS) test is not practical to apply, researchers have suggested different indirect test methods for determination of tensile strengths of rock materials. However, all the indirect tensile strength test methods have important discussions on the validity of the results obtained with them and/or important problems resulting from specimen preparation and loading mechanisms impracticality (Gercek and Ozarslan 2011, Komurlu and Kesimal 2012, Coviello *et al*. 2005).

To shortly deal about a testing method written above, it can be said that the ring method suggested by Hobbs has similar problems with those of the Brazilian test. On the other hand, Luong method that needs to sensitively use three different core sampler sizes has many limitations in failure validity, and Hoek & Brown method that needs specific hydraulic loading devices is also not a practical and popular testing way. Additionally, the tension effect supplied by the hydraulic confinement pressure induces triaxial stress distribution which is another problem making the Hoek & Brown test to be not usable for measuring the uniaxial tensile strength value.

It is not a valid way to measure the uniaxial stress using indirect methods that cause three-axial stress distribution in critical locations for maximum tensile stress induced. The inconsistencies between the results obtained with different ITS determination methods confirm that there are additional factors that significantly affect the results of ITS tests in addition to the strength of the tested materials. Many reasons as written above indicates the importance to apply direct tensile strength (DTS) testing methods.

Because of a possible failure in the junction parts of rock specimen, adhesive and steel cap instead of rock material specimen, the gluing and holding problems are important reasons to not apply the conventional direct tensile strength (DTS) test. Especially, it is quite hard to carry out conventional DTS test for rock materials with high strength values. In this study, a new approach for solving the holding problem of conventional DTS determination methods was investigated whether lathed rock core specimens can be used for supplying a proper holding mechanism. The lathe process supplies a dog bone shaped rock specimens that let to be easily held using a steel ring to apply direct tension load.

In this study, it is aimed to suggest ideal shape of lathed DTS test specimens for valid failure under the control of uniaxial tensile stress condition. To determine ideal geometry for a valid failure of rock materials, both numerical and experimental analyses were carried out in this DTS test study.

2. Numerical modelling study

2.1 Methods in numerical modelling study

A series of Finite Element Analyses (FEM) was performed by using ANSYS software to investigate the stress distribution in a lathed (dog bone shaped) DTS test specimen. Eight-node solid brick elements (Solid65) were used for three-dimensional modeling of rocks, which have the capability of cracking in tension, crushing in compression, plastic deformation, and three degrees of freedom at each node, including transition in the nodal x, y, and z directions. The elasticity modulus of models was assumed to be same for the tension and compression. The modeled material was defined as linear elastic material in this study.

The models predicted the failure of brittle materials according to the Willam–Warnke failure criterion used for concrete, rocks and other cohesive-frictional materials, such as ceramics (Willam and Warnke 1974). Material of the steel holding ring apparatus was modeled with Solid185 as rigid steel with 400 GPa modulus of elasticity. The contact surfaces between the rock and steel holding ring apparatus were simulated with the Conta174 and Targe170 contact pairs. The friction coefficient between rock and steel of the loading apparatus was considered as 0.3 for all analyses.

Static analyses were performed for each of the models. For displacement-controlled loading, loads were divided into multiple substeps until the total load was achieved. Stress distributions and cracking mechanisms for all specimen models were plotted. Input parameters of the various rock material models are given in Tables 1 and 3. The dog bone shaped rock models had the maximum diameter (d_{max}) of NX core size that is widely used and two different minimum diameters (d_{min}) of 3.2 cm and 4.3 cm for two different cutting depths. Different rock samples were modelled to have four different cutting angles of angular part (α) of 0°, 27°, 45°, 63° as seen in Fig. 1.

This new method was proposed to suggest a new holding mechanism to apply DTS test obeying the suggestions by the International Society for Rock Mechanics (ISRM). Ratio of length of the part with diameter value of d_{min} to d_{min} of the lathed cylindrical parts of the models was between 2.5 and 3 as suggested by ISRM (2007). The mesh length in the rock models which was chosen to be 1 mm is also parallel to the ISRM suggestion stating that the diameter of specimen should be higher than 10 times of the particle size of the largest grain in rock. In addition to the

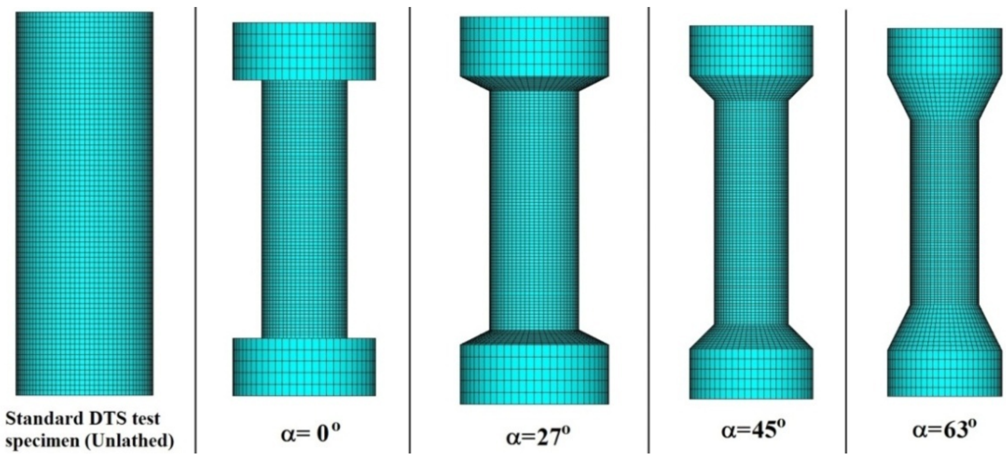


Fig. 1 DTS test specimen models

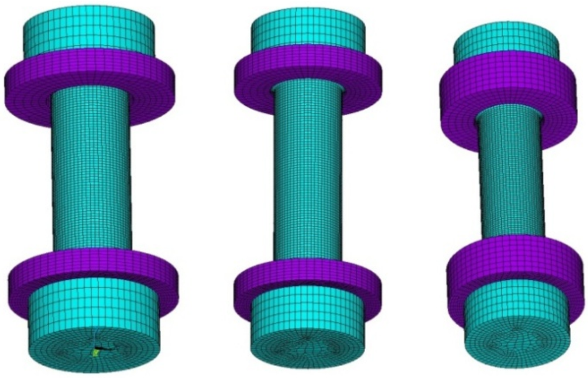


Fig. 2 Some lathed specimens with holding ring models for $\alpha = 27°$ (left), $\alpha = 45°$ (mid), $\alpha = 63°$ right) conditions

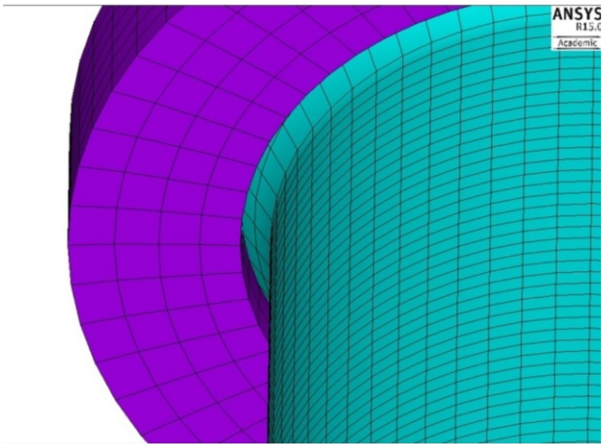


Fig. 3 Steel holding ring touching to the lathed rock sample

lathed specimen models, standard cylindrical DTS test specimen with diameter of NX core size was modelled and analysed to compare the results obtained using it with those obtained with the lathed models.

The holding steel rings were modelled to have same α angles with those of the rock sample models and contact through the angular cut part of the lathed specimens (Fig. 2). The minimum inner diameter size of steel rings was 2 mm bigger than d_{min}, the minimum diameter of core sample lathed, hence there is 1 mm gap from rock surface to inner surface of steel ring at the edge of the angular cut part (Fig. 3). On the other hand, load was applied from the top and down parallel surfaces of the standard DTS specimen to apply tension representing gluing on the surfaces.

2.2 Numerical modelling study results

The stress distribution in models, critical failure locations for different models, failure load and determined tensile strength values were investigated considering the results of the analyses. According to the results obtained with this study, critical part for crack initiation was seen to be

Table 1 Material properties of rock model 1

Compressive strength	Tensile strength	Modulus of elasticity	Poisson's ratio
100 MPa	10 MPa	50 GPa	0.3

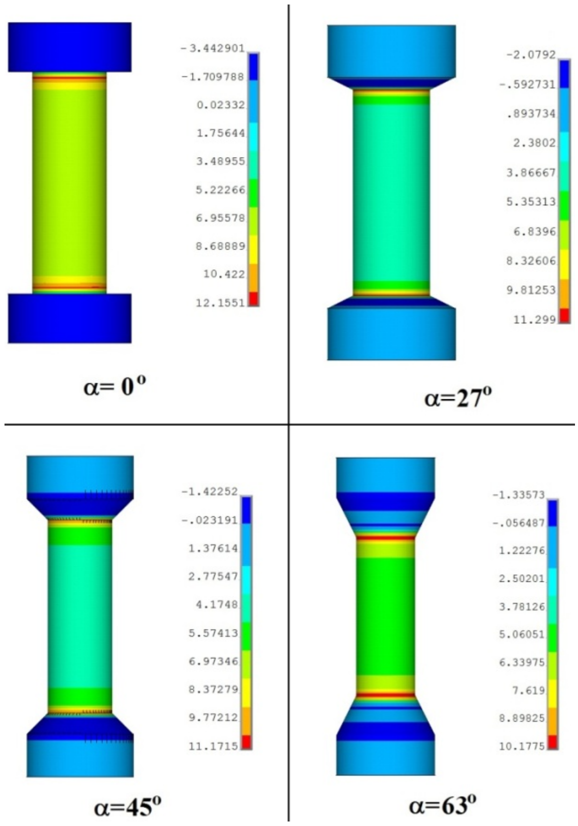


Fig. 4 Major principle stress distribution

the edge of the angular cut part because of increase in the horizontal tensile stresses occurrence as a result of the change in diameter of the angular part. As seen in Fig. 4, the most ideal model for crack initiation under uniaxial tensile stress conditions was found to be the model having less increasing ratio of angular cut part diameter, which is α = 63° condition. It is found from the numerical models that the minor principle stress values decrease and majority of the maximum principle stress increases as the α angle increases. Therefore, ability to fail under a practically uniaxial stress distribution gets better with an increase in the α angle.

Stresses at critical locations of maximum tension are given in Table 2 to clarify the crack initiation of models. In Table 2, 0, 27, 45 and 63 respectively refer α angles of 0°, 27°, 45° and 63°, 3.2 refers d_{min} value of 3.2 cm and 4.3 refers d_{min} of 4.3 cm.

As stress distribution through the length of the lathed cylindrical parts with diameter of d_{min} value was constant for a long part, further models were analyzed to investigate whether the shortened length of the specimen can be used instead of the models made considering the size suggestions by the ISRM. Further models with length of the lathed cylindrical part with the

Table 2 Stresses at critical locations of maximum tension and uniform stress zone (values for Rock Model 1, $\sigma_{t\max}$: maximum tensile stress at the crtical edges, σ_{hc}: horizontal stress at the critical edges, σ_{tu}: tensile stress at the uniform stress zone, σ_{tuh}: horizontal stress at uniform stress zone, *s*: shortened)

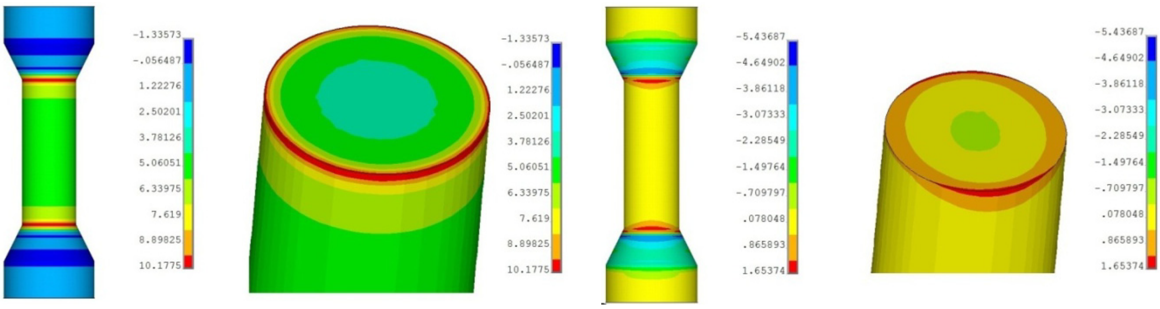
Model name	$\sigma_{t\max}$	σ_{hc}	σ_{tu}	σ_{tuh}
0-3.2	12.15	3.40	6.96	-0.25
27-3.2	11.30	3.73	3.87	-0.29
45-3.2	11.17	3.03	4.17	-0.43
63-3.2	10.18	1.65	5.06	-0.08
63-3.2-s	10.66	2.01	5.01	-0.14
0-4.3	12.38	3.70	3.94	-0.30
27-4.3	13.03	4.08	3.96	-0.11
45-4.3	11.74	4.15	3.81	-0.49
63-4.3	10.45	1.70	4.63	-0.10
63-4.3-s	11.17	1.67	4.94	-0.28

Table 3 Material properties of different models

Model	*E* (GPa)	*v*
Model 1	50	0.3
Model 2	10	0.3
Model 3	100	0.3
Model 4	50	0.2
Model 5	50	0.4

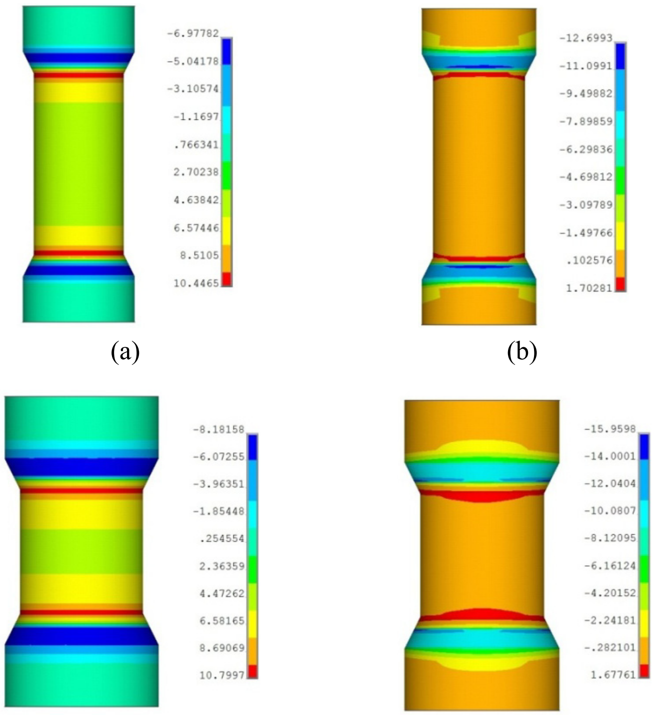
diameter of $d_{\min}$ of 5.4 cm (NX size core diameter) were analyzed in this study. It was seen from the shortened specimens that stress distribution at the critical tension region is not significantly changed and the stresses at the mid parts having uniformed stress distribution are practically same with those of the long models. As the DTS results did not change shortening the specimens, 5.4 cm length of lathed cylindrical part with the diameter of $d_{\min}$ was found to be convenient for not changing the stress distribution at the critical edges because of their no influence on each other, where is the ends of the lathed cylindrical parts with the diameter of $d_{\min}$. As an example, Fig. 6 shows the stress distributions in long and shortened models with α angle of 63° and $d_{\min}$ of 4.3 cm.

According to the numerical modelling results, a possible failure is expected to initiate at the critical edges for all the models, which has non-uniform stress distribution in the cross-section (Fig. 5). It should be noted herein that all the models were found to have a critical zone which has non-uniform stress distribution and maximizing tensile stress values at the outer part of the cross-section. Also, all the models were seen to have a uniformly distributed stresses zone in an interval on the mid of the lathed part. As seen in Fig. 7, the uniform tensile stresses at the cross-section of mid of the lathed part was found to be half of the tensile strength and nearly half of maximum tensile stress induced in case of 63° α and 3.2 cm $d_{\min}$. Different material models with the uniaxial tensile strength of 10 MPa were modelled to test whether the uniform tensile stress is also 5 MPa when the further models are failed due to reaching the tensile strength at the critical zone of angular part edges. Material properties of the further models are given in Table 3.



(a) (b)

Fig. 5 (a) Vertical stress distribution; (b) horizontal stress distribution in the model with α angle of 63°, cross-sections of the critical edge (right)



(c) (d)

Fig. 6 Stress distributions in long and shortened models with α angle of 63° and d_{min} of 4.3 cm ((a) & (c) show vertical stress; (b) & (d) show horizontal stress)

The stress differences between the critical zone and zone of uniformly distributed stress (mid of the lathed length) were found to be same for all the models with α angle of 63° and d_{min} of 3.2 cm that the uniform tensile stress is 5 ± 0.5 MPa when tensile strength is reached at the critical zone (edge). As a result of induced horizontal stresses at the critical zone, models failed at 10.65 ± 0.3 MPa instead of 10 MPa. Because all the models with α angle of 63° and d_{min} of 3.2 cm failed when uniform stress at the mid part of the lathed length is half of the DTS value, Eq. (1) is suggested to

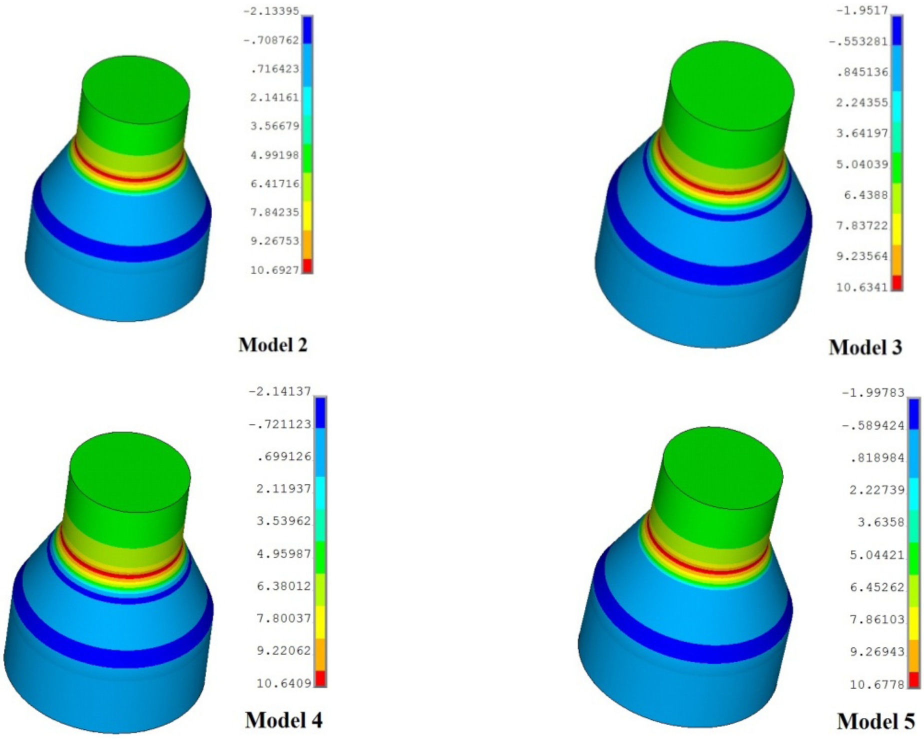


Fig. 7 Major principle stresses in different rock material models with α of 63° and $d_{\min}$ of 3.2 cm

use for DTS calculations of rock materials considering two times of the maximum loads for failure (F_m) and the cross-section area with the diameter of $d_{\min}$. As the Eq. (1) is suggested for the models with $d_{\min}$ of 3.2 cm, Eq. (2) can be derived writing the $d_{\min}$ value.

$$DTS = 2F_m / (\pi (d_{\min})^2 / 4) = 2.55 F_m / (d_{\min})^2 \quad (1)$$

$$DTS = 2.55 F_m / (10.24 \text{cm}^2) \quad (2)$$

Compressive strength and tensile strength values are same for all models, only deformation characteristics of the models were changed by the variations in Modulus of Elasticity (E) and Poisson's ratio (v). The material properties of different models are given in Table 3. The failure

Table 4 Failure load and DTS values measured from shortened (s) models with α of 63° and $d_{\min}$ of 3.2 cm

Model name	F_m (N)	DTS (MPa)
Model 1	4299	10.71
Model 2	4312	10.74
Model 3	4279	10.66
Model 4	4288	10.68
Model 5	4291	10.69

load and calculated tensile strength values using Eq. (2) are given in Table 4.

As seen in Table 4, 7% higher DTS values than the uniaxial tensile strength of the models were calculated analyzing the models. Therefore, it is suggested to modify the results multiplying by 0.93 to prevent overestimating the value of uniaxial tensile strength as given in Eq. (3)

$$DTS = 0.93(2.55F_m/(10.24\text{cm}^2)) = 0.23F_m/\text{cm}^2 \quad (3)$$

3. Experimental study

3.1 Methods in experimental study

A series of tensile strength tests was carried out on dog bone shaped specimens made from three different groups of rock material consisting of tuff, dacite and basalt type rock materials and a cementitious rocklike material. The rock samples were selected carefully and the core samples were taken for the experiments. After visual observations, core samples having no fractures, cracks, fill joints etc. were chosen and prepared to use in tensile strength testing. The unlathed cylindrical specimens were also tested in the experimental study to investigate whether relation between the strength results obtained with lathed specimens and standard specimens is parallel with the results obtained with numerical analyses. With the experimental study, Eq. (3) is investigated to assess whether it is usable for DTS determination. To prepare specimens with the geometry of Model 63-3.2 in numerical analyses, a guide plate was cut as seen in Fig. 8. Using the guide plate, the cutting

Fig. 8 A reference plate to prepare specimens with the geometry of Model 63-3.2

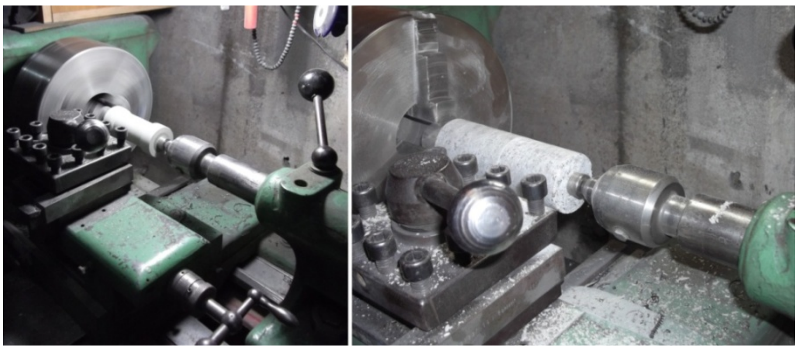


Fig. 9 Lathe machine process

angle and depth were controlled in the lathing process. Rock core specimens with the diameter of NX core size were used to prepare dog bone shaped rock specimens using lathe machine (Fig. 9). An example of lathed specimen prepared to have the geometry of the model with α of 63° and d_{min} of 3.2 cm (Model 63-3.2) is shown in Fig. 10.

Cementitious rocklike mix was produced having a water to cement ratio of 45%. Fine aggregate with smaller particle size than 4 mm was used in the mix since bigger particles were thought to cause inhomogeneity in the specimen cross-section. In the mix, aggregate was used having three times of cement amount by weight. Ordinary Portland cement (OPC), aggregate and water were mixed thoroughly in a mixer tank with the volume of 14 liters for 7 minutes. Then, specimens were cast into molds manufactured to have the shape of Model 63-3.2 (Fig. 11). Additionally, cylindrical specimen molds with 54.7 mm inner diameter and 140 mm height were manufactured to prepare cement mix specimens to be used in the conventional DTS tests. Cement mix material was cast in three steps, and air was removed with the tamping rods after each casting

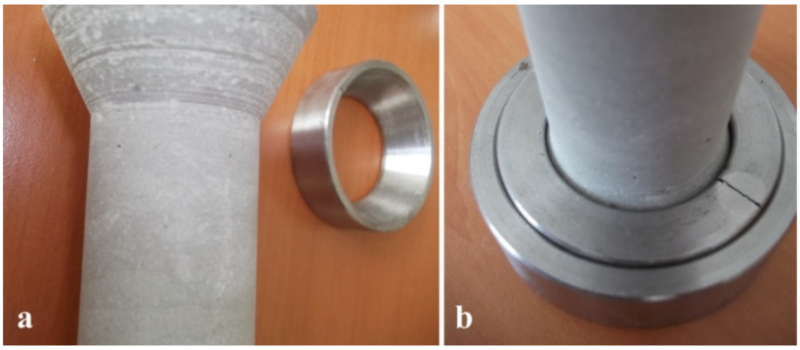


Fig. 10 (a) Specimen prepared to have the cutting geometry of Model 63-3.2; (b) semi-circular pairs contacting to specimens

Fig. 11 (a) Mold design; (b) casting mix into the molds; (c) tamping; (d) a specimen in mold; (e) rocklike material specimens with α angle of 63° and d_{min} of 3.2 cm steps. Cement mix specimens were also put on vibration table for 1 minute to remove air bubbles and increase homogeneity. The cement mix specimens were removed from molds after 24 hours and cured for 8 days before tests.

To hold the specimens, a steel holder cap setup (couple) was manufactured as seen in Fig. 12. The holder cap design used in this study consists of angular cut semi-circular pairs that contact to the specimens, rings to be inserted semi-circular ring pairs and the frame cap (Fig. 12(a)). The Tensile strength values of all type of rock materials were also determined in the conventional

Fig. 12 (a) Steel holder frame cap; (b) and (c) semi-circular ring pair and rings to be inserted semi-circular ring pairs; and (d) steel holder cap setup

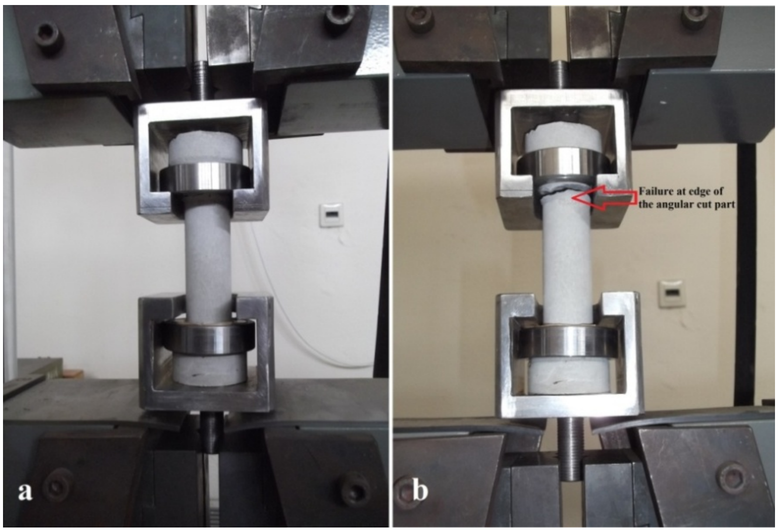


Fig. 13 (a) Lathed specimen testing; (b) failure at the edge of angular cut part

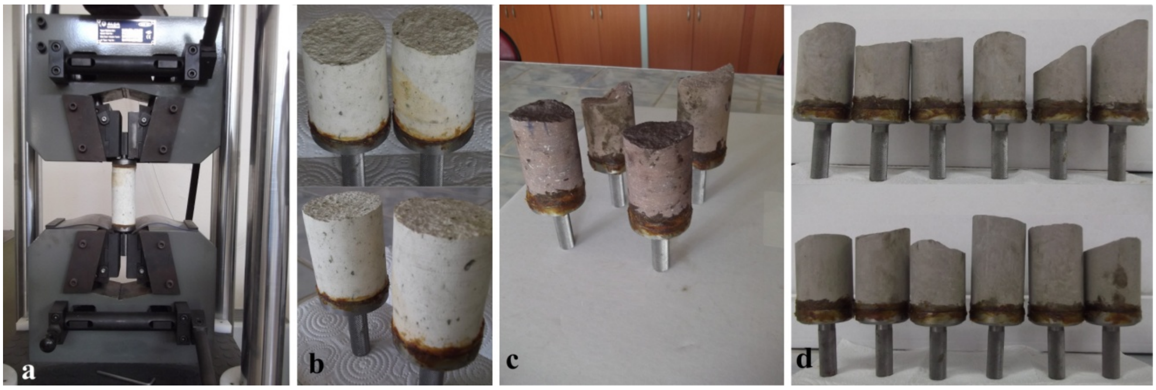


Fig. 14 (a) Direct tensile strength test of cylindrical specimens; (b) failed tuff specimens; (c) failed dacite specimens; (d) failed rocklike specimens

cylindrical specimen test method. Using a strong epoxy based adhesive, rock specimens with the diameter of NX core size were glued to steel caps which had been manufactured to be held by tension test equipment. As parallel to the ISRM suggestion, the loading rate was chosen to be 0.2 kN/sec for both dog bone shaped and standard cylindrical tensile strength test specimens. Direct tensile strength testing and some of failed standard cylindrical specimens are shown in Fig. 14.

Table 5 DTS values obtained from lathed specimens

Specimen type	Specimen name	σ_{td} (MPa)
Rocklike material	Replicate 1	1.82
	Replicate 2	1.66
	Replicate 3	1.64
	Replicate 4	1.73
	Replicate 5	1.81
	Mean	**1.73**
Tuff	Replicate 1	1.62
	Replicate 2	1.39
	Replicate 3	1.46
	Mean	**1.49**
Dacite	Replicate 1	3.63
	Replicate 2	3.94
	Replicate 3	4.11
	Mean	**3.89**
Basalt	Replicate 1	7.07
	Replicate 2	6.89
	Replicate 3	6.51
	Mean	**6.82**

Table 6 DTS values obtained from standard cylindrical specimens (IF: invalid failure at the adhesive part)

Specimen type	Specimen name	σ_{td} (MPa)
Rocklike material	Replicate 1	1.82
	Replicate 2	1.71
	Replicate 3	1.77
	Replicate 4	1.95
	Replicate 5	1.89
	Replicate 6	1.98
	Mean	**1.85**
Tuff	Replicate 1	1.49
	Replicate 2	1.61
	Mean	**1.55**
Dacite	Replicate 1	3.53
	Replicate 2	3.86
	Mean	**3.70**
Basalt	Replicate 1	IF
	Replicate 2	IF
	Replicate 3	IF
	Mean	-

Table 7 Ratios between strength values of cylindrical and lathed specimens

Specimen	σ_{tc}/σ_{td}
Rocklike material	1.07
Tuff	1.04
Dacite	0.95
Basalt	-

3.2 Experimental study results

The results obtained with the experimental study are given in Tables 5-7. As same in the observations from numerical analyses, failure of dog bone shaped lathed specimens initiated due to the crack occurrence at the edge of angular cut parts. Strength values of the cylindrical standard specimens of the basalt type material could not be determined under conventional test method, because of having failure at the adhesive part instead of rock material. The results of this study confirm that high strength materials are able to be tested with the new method of dog bone shaped specimens usage. Considering the Eq. (3) derived in accordance with the numerical analyses, experimental results are accepted to be parallel to those obtained with the numerical analyses. As seen in Table 7 including ratios between strength values of lathed specimens (σ_{td}) and cylindrical specimens (σ_{tc}), experimental and numerical results were found consistent.

4. Conclusions

Dog bone shaped DTS test specimens used for different brittle materials such as concretes, cements and ceramics were investigated to be also used in rock material testing in this study. According to the results, dog bone shaped and lathed rock specimen with α angle of 63° and $d_{\min}$ of 3.2 cm was assessed to have the most ideal sample geometry for obtaining accurate results for different rock materials modelled in this study. To calculate DTS of rock materials, Eq. (3) is suggested to use in case of testing dog bone shaped test samples with α angle of 63°, $d_{\min}$ of 3.2 cm and $d_{\max}$ of the NX core size of 5.4 cm.

As an advantage of the method, the DTS value was not found to change with the change in rock material deformability and other properties contrary to Brazilian test having deficiencies in the contact conditions and stress distribution variations due to the change in the rock material (Markides *et al*. 2012, Komurlu *et al*. 2016b, Erarslan and Williams 2012).

The reason for considering the uniaxial stress distribution to select an ideal α angle is suggesting a standard ratio between the results obtained from conventional DTS determination test and use of dog bone shaped specimens. The biaxial stress distribution at the critical zone can cause differences in the failure load depending on the material properties such as internal friction angle changing the biaxial strength values (Chen and Stimpson 1993, Komurlu 2012, Bagheripour *et al*. 2011). The stress distribution in the specimen with α of 63° can be practically accepted to be uniaxial that is proper to carry out DTS tests.

According to the ISRM suggestions, length to diameter ratio of DTS test specimen should be between 2.5 and 3 (ISRM 2007). It is seen in this study that the length of the part with diameter of $d_{\min}$ should be higher than a length which is enough to eliminate the influence of the stress distribution at the angular part edges on each other, to supply a practically uniaxial stress distribution at the critical edges and perfectly uniformed stress distribution at the mid of the length of the part with diameter of $d_{\min}$. Length of the lathed part with diameter of $d_{\min}$ of 5.4 cm was found to be applicable although the horizontal stress concentration slightly increases with the decrease in the length from 8.6 cm supplying length to diameter ratio of 2.7 that is suggested by the ISRM. Because the crack initiation mechanisms and locations are different for the conventional DTS test and the method investigated in this study, the ratio of length to diameter was found acceptable to be different than that suggested by the ISRM.

ISRM suggests the minimum diameter requirements for the direct tensile strength specimens in consideration of the maximum grain size in the rock materials. ISRM suggests using diameters which are minimum ten times higher than the maximum grain size in tested rock material (ISRM 2007). In addition to the strength parameter of the rock materials, ITS values are dependent on other material properties such as deformation characteristics (Komurlu *et al*. 2016b, Markides and Kourkoulis 2016). To eliminate the problems in ITS determination and non-practicality of the holding in conventional DTS test, a new testing method to obtain DTS values is believed to contribute much to the rock testing area.

Because of having the stress distribution which can be practically accepted to be uniaxial, the stress distribution at the critical edges was found to be more convenient as the α angle increases. However, the holding problem is to be faced as the angle increases excessively. As confirmed by the experimental study, α angle of 63° is convenient to have no holding problems in the tests of both soft and hard rock materials. The contact of the holder rings and lathed specimens should be paid attention to be regular for preventing misalignments and applying stress uniformly (Kourkoulis 2012, van Mier and van Vliet 2002). Otherwise, an early failure under the control of concentrated stresses is predicted to have an invalid test. Therefore, it is important to carefully place the steel ring pairs on the lathed specimens made with correct geometry and dimensions.

As a disadvantage of the method, cracking resulting from lathe process should be considered to be a reason of need for time-consuming process. It should be noted herein that a basalt specimen could not be prepared because of cracking during the lathe process. Specimen preparation by lathing should be carried out carefully, by increasing cutting depth slowly to be not faced with rock cracking. Depending on the rock brittleness, the lathing process can take more than 10 minutes for preparation of a specimen without having cracking.

According to the results obtained with this study, new researches on the dog bone shaped rock specimen testing are suggested to go further for improving the method to be a standard way to determine DTS values of rock materials. In conclusion, Eq. (3) is suggested to use for calculation of DTS values of the dog bone shaped rock material specimens in the geometry of model 63-3.2, as confirmed by both numerical and experimental data.

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