Geomechanics and Engineering, *Vol. 23, No. 2 (2020) 165-178*
DOI: https://doi.org/10.12989/gae.2020.23.2.165

The effect of jaw's curvature on Brazilian tensile strength of rocks

Halime Yousefi[a] and Davood Fereidooni*

School of Earth Sciences, Damghan University, Damghan, Iran

(Received April 20, 2020, Revised August 25, 2020, Accepted September 28, 2020)

Abstract. This paper investigates the effect of the jaw's curvature, also known by contact angle and jaw arc central angle (2α), of the Brazilian test apparatus on indirect tensile strength of various rock types. That's why, ten rock samples including limestone, marble, skarn, granite, diorite, and granodiorite were collected from some quarries in different provinces of Iran. Petrographic, mineralogical and textural investigations were performed using thin section analyses. Physical properties of the selected rock samples namely dry and saturated unit weights, porosity, water absorption, and specific gravity were determined for the rock samples. In addition, Brazilian tensile strength at different 2α angles (i.e., 2α = 0°, 10°, 15°, 20°, 45°, and 60°) were determined for the rocks in the laboratory. Results show that the parameter for the rocks is between 3.81 MPa at 2α=0° and 54.76 MPa at 2α=60°. This means that Brazilian tensile strength increased with increasing 2α angle from 0° to 60°. Also, it was found that the highest change rate of the Brazilian tensile strength occurs in range of 2α=15°−30° for most studied rock samples. In some tested samples, the parameter is decreased only at 2α = 60°. The values of Brazilian tensile strength of the rocks tested by flat and standard jaws are near to each other.

Keywords: rock sample; Brazilian test; tensile strength; jaw curvature; contact angle; 2α angle

1. Introduction

The Brazilian test, known as diametrical compression test, indirect tensile strength test, splitting test, and split-tension test, is an indirect testing method for determining tensile strength of rocks and rock-like brittle materials such as concrete (Li and Wong 2013). This simple test method is used on cylindrical and flat disc-shaped specimens as well as cubes or prisms (Rocco *et al.* 2001). The Brazilian test can be done using a compression machine and specimens identical in shape and geometry the same as ones are used in uniaxial compression test (García *et al.* 2017). The development process of the Brazilian test can be divided into three separate phases. The first phase began in 1943 when Carneiro presented this test method for determining tensile strength of concrete (Carneiro 1943). This phase continued until 1977 when the International Society for Rock Mechanics (ISRM) issued a suggestion method for its determination on rocks ISRM (1977). Afterwards, in the period from 1978 to 1991, the second phase was characterized by the use of the standardized method of the Brazilian test. The third phase started in 1991 and continues today. This phase is reflected by the improvements and toward betterments of the primary testing method (Briševac *et al.* 2015). Despite going through the above three phases, there is not available a definite and unique method for loading disc-shaped rock specimen in the test about eight decades after proposing the test method. Even today, the two standardized techniques suggested by ISRM (2007) and proposed by the American Society for Testing and Materials (ASTM) (ASTM 2008) that adopt jaws with different shapes for loading rock specimens. Brazilian tensile strength test is a research interest for a number of outstanding scholars in the recent years. So that, many researchers (e.g., Barla and Innaurato 1973, Istvan *et al.* 1997, Seto *et al.* 1997, Aonoa *et al.* 2012, Dan *et al.* 2013, Khanlari *et al.* 2014, Khanlari *et al.* 2014, Komurlu and Kesimal 2015, Tan *et al.* 2015, Fereidooni 2016, Markides and Kourkoulis 2016, Huang *et al.* 2017, Tutmez 2017, Burkhardt *et al.* 2018, Wei *et al.* 2019) have determined the tensile strength of rocks by this method. In this way, many studies (see Li and Wong (2013)) have also focused on the loading jaws and contact area for the Brazilian test to determine the optimum load transfer to the specimen such that tensile stresses develop evenly in the central region and minimize crushing at the edge of the specimen (Perras and Diederichs 2014). This is one of the most notable topics for evaluating indirect tensile strength of rocks. Perras and Diederichs (2014) have presented a comprehensive review concepts and testing method of the tensile strength of rocks. Komurlu and Kesimal (2015) described the evaluation of indirect tensile strength of rocks using different types of jaws including flat jaw, ISRM standard jaw (2α=10°) and jaws with contact angle of 2α=15° and 30°. In their research, a series of Brazilian tests were conducted using specimens prepared from NX size cores, and the effect of contact angle and loading condition on indirect tensile strength were investigated for various rock types such as limestone, marble, dacite, riodacite, basalt and andesite. Markides and Kourkoulis (2016) have investigated the influence of jaw's curvature on the results of the Brazilian

*Corresponding author, Ph.D.
E-mail: d.fereidooni@du.ac.ir
[a]M.Sc. Student
E-mail: hlm.yousefi@gmail.com

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

Fig. 1 Sample locations on the general map of Iran

test in a detailed study. García *et al.* (2017) found that the Brazilian tensile strength is related to loading geometry overall, the parameter is different at 2α angels of 5°, 10°, 12°, 22°, and 25°.

With all these interpretations, the Brazilian test, based on ISRM (2007) standard, has two concave jaws with arch diameter of 8.1 cm, which is equal to 1.5 time of the diameter of a NX-sized core specimen. In beginning of loading, the force applied by the jaw to the specimen can be identified linear for the standard jaws the same as flat jaw. During the test as the force increases, two rectangular contact area creates between the jaws and the specimen once the specimen deforms (Jaeger *et al.* 2009). This state is correct for both standard and flat jaws. Aonoa *et al.* (2012) analytically assessed the contact angle issue. It is clear that the contact area of standard and flat jaws changes according to the specimen hardness, jaw rigidity and load value. Hondros (1959) investigated the Brazilian test for a thin disc-shaped specimen loaded by uniform pressure applied radially over a short strip on the circumference at each end of the specimen with a definite contact angle (2α). He found that maximum tensile stress is induced in the center of specimen under a load with a certain 2α angle. Fairhurst (1964), adopting an empirical generalization of Griffith's criterion and agreeing the Hondros (1959) approach, quantitatively discussed the validity of the Brazilian test in accordance with the boundary conditions. He studied the role of the loaded rim's length and found that, increasing the contact angle, fracture could start away from the disc's center and proposed an optimum semi-contact angle α equal to about α= arc tan(1/8). Mellor and Hawkes (1971) assessed also the effect of the actual distribution of radial stresses, which it should not be considered uniform. Moreover, they proposed possible methods for reducing the contact (friction) stresses. In their study, the use of curvature jaws with radius more than the radius of applied specimen is suggested for the first time. Erarslan and Williams (2012) obtained more accurate results with curvature jaws possessing the same radius as applied disc-shaped specimen with a certain contact angle than those obtained from ISRM standard jaws. They found that the contact angle affects the fracture toughness of the disc-shaped specimen so that toughness increases with increasing contact angle.

The effect of friction between jaws and disc-shaped specimens is also important in association with fracturing behaviors of the specimens in the Brazilian test (Lanaro *et al.* 2009, Kourkoulis *et al.* 2013a, b). When the jaws provide uniformly radial stress, the friction effect at the center of a specimen is virtually negligible. However, failure can start in the compression area due to the induced shear stresses beneath the loading jaws. On the other hand, the effect of friction is not negligible for non-uniformly radial stress. Markides *et al.* (2012) noted that radial stress has to be considered as non-uniform for obtaining true outcomes. Markides *et al.* (2010), Markides *et al.* (2012) and Kourkoulis *et al.* (2013b) have presented comprehensive analytical studies on contact friction and its influences on the stress distribution and deformation behaviors of disc-shaped specimens under uniform and non-uniform loads. Recently, the effect of boundary conditions on the Brazilian test results is confirmed by many other researchers (e.g., Ma and Huang 2018, Aliabadian *et al.* 2019, Yousefi 2019).

Given the above inferences, the contact angle or 2α angle is an important factor, which is dictated by the curvatures of the jaws, in the Brazilian test. In the present research, an attempt has been made to quantify the effect of this factor on essential aspects of the Brazilian test by using some rock samples collected from different parts of Iran. Simultaneous testing of various rocks from three groups of rocks namely sedimentary, metamorphic, and igneous at six different 2α angles have been considered in our research that testing of the rocks at 2α angle equal 45° and 60° is rarely found in previous research works. Also, investigating the rate of changes in the values of Brazilian tensile strength of the rocks with increasing 2α angle is performed for the first time and a parameter called change ratio (CR) is proposed in this research. These can be novelties for the research.

2. Methodology

2.1 Sample selection

The number of ten rock samples including three sedimentary (limestone), three metamorphic (marble and

Table 1 Names of the rock samples and their information

Rock mark	Name	Province / City	Quarry name
KHL	Khoram-Abad Limestone	Lorestan / Khoram-Abad	Gohareh
ARL	Arsanjan Limestone	Fars / Arsanjan	Toos Tavoos
BJL	Bajestan Limestone	Khorasan Razavi / Bajestan	Samenolaemeh
NRM	Neyriz Marble	Fars / Neyriz	Tangehana
MHM	Mahallat Marble	Markazi / Mahallat	Bagher Abad
BRS	Birjand Skarn	Khorasan Jonoobi / Birjand	Gorid
KDG	Khoram Darah Granite	Zanjan / Khoram Darah	Alvand 1
NBG	Nehbandan Granite Gneiss	Khorasan Jonoobi / Nehbandan	Chahdashi
NTD	Natanz Diorite	Yazd / Natanz	Granite
NTG	Natanz Granodiorite	Yazd / Natanz	Ooreh

Fig. 2 Specimen preparation; (a) and (b) selected rock samples, (c) the used machine for coring the samples, (d) the rock blocks after coring, (e) the prepared disc-shaped specimens and (f) wrapping the paper glue around the specimens

skarn), and four igneous (granite, granite gneiss, diorite and granodiorite) were collected from quarries in different provinces of Iran. These samples frequently served as building stones in facades, curb, and flooring stones in many cities within Iran. They are various in color, luster, surface texture, and other apparent features. Fig. 1 depicts the sample locations on the general map of Iran and Table 1 summarized the rock sample information.

2.2 Specimen preparation

Laboratory disc-shaped specimens were prepared from the selected samples for considered tests. Fig. 2 displays specimen preparation process in the laboratory. The diameters of the prepared rock specimens were 54 mm obtained by a coring machine. A total of 600 specimens were used for various destructive and nondestructive tests. The ratio of length to diameter of the prepared disc-shaped specimens was in accordance with ISRM (2007) namely 0.5 to 0.75.

2.3 Test procedure

The laboratory investigations determined mineralogical and petrographic characteristics, physical properties, and Brazilian tensile strength (BTS) at different 2α angles. Fig. 3 presents test plan for mineralogical and petrographic, physical, and Brazilian tests in the present study. In this regard, polished thin sections were prepared for optical microscopy to identify the mineral composition, petrographic properties, and texture of the rock samples based on ISRM (2007). The disc-shaped specimens were provided to determine physical properties. The properties include dry and saturated unit weights, effective porosity, water absorption, and specific gravity, that they were determined for the rocks based on ISRM (2007) suggested methods. The number of tested specimens of each rock sample for determining the physical properties was five specimens.

Brazilian tensile strength (BTS) of the selected rock samples is obtained according to ISRM (2007). The

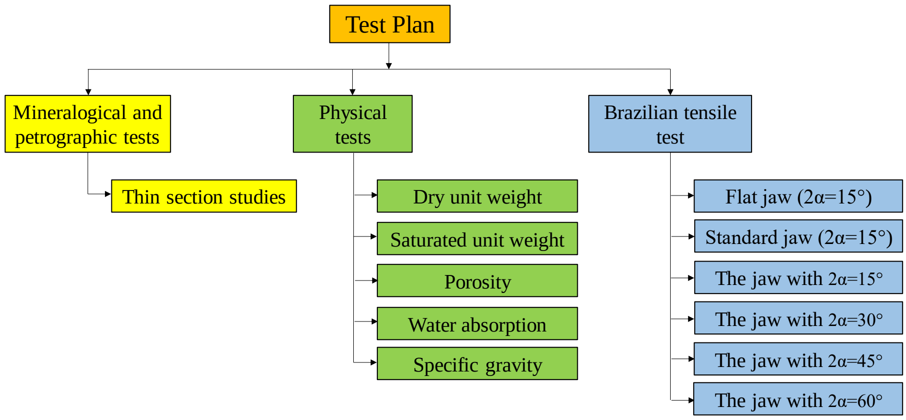

Fig. 3 Test plan for mineralogical and petrographic, physical, and Brazilian tensile tests

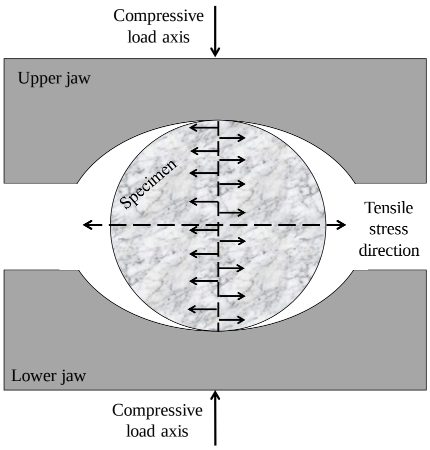

Fig. 4 Tensile stress direction in Brazilian test

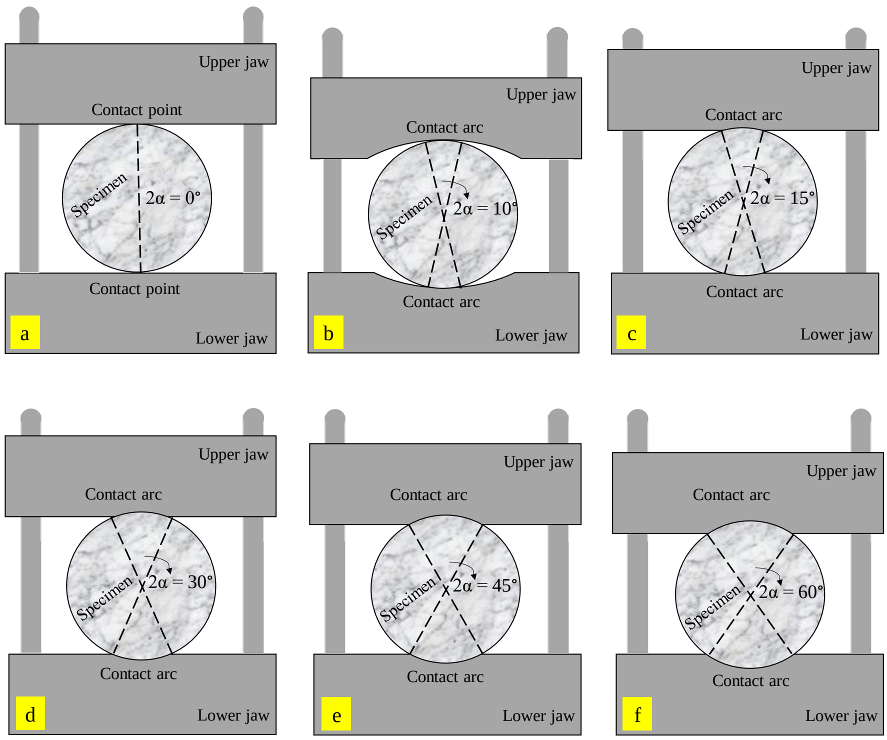

Fig. 5 Different 2α or contact angles in the present research; (a) 2α=0° (flat jaw), (b) 2α=10° (standard jaw), (c) 2α=15°, (d) 2α=30°, (e) 2α=45° and (f) 2α=60°

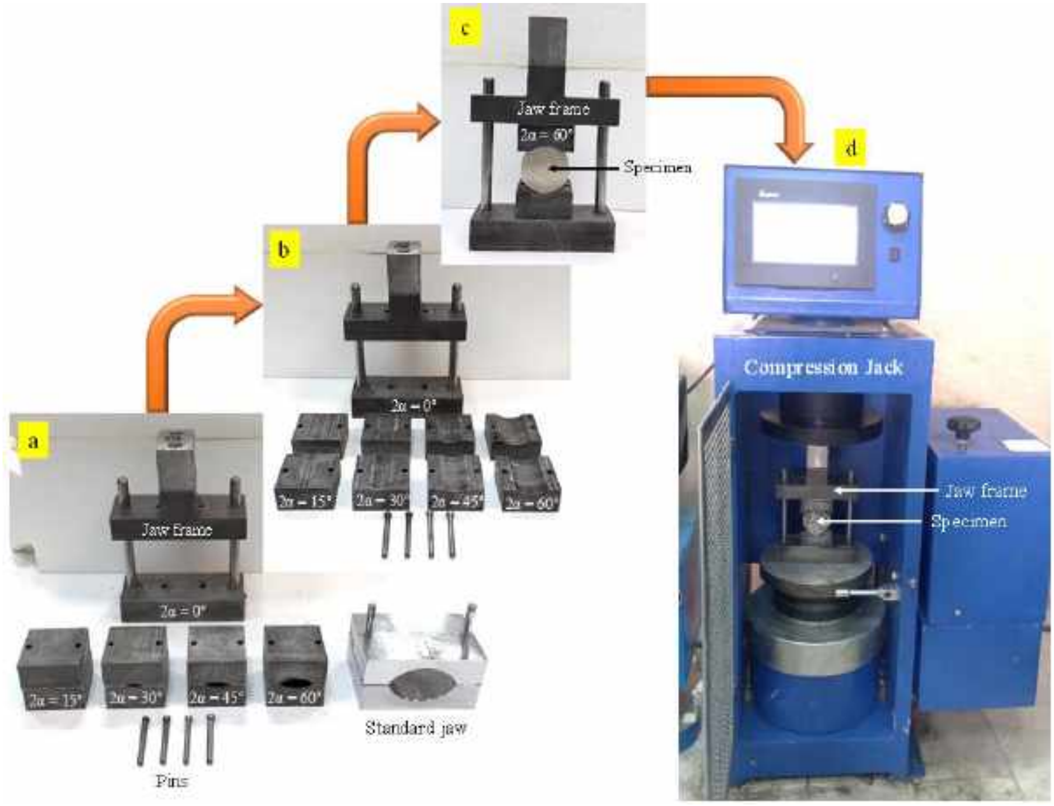

Fig. 6 Brazilian tensile strength test apparatus and its performance process in this research; (a) and (b) built Brazilian jaws from MO40 steel in different contact angles and its comparison to standard jaw, (c) placement specimen into jaws and (d) insert jaw frame containing specimen into test machine

Brazilian tensile strength test can be carried out on disc-shaped specimens of rocks with thickness to diameter ratio (t/D) of 0.5 or between 0.2 and 0.75 in accordance with ISRM (2007) and ASTM (2008), respectively. In the test, tensile stress is perpendicular to compressive load axis. Forasmuch as the load axis is always upright, tensile stress can be calculated on the horizontal direction (Fig. 4). The tensile stress is maximum at the center of the disc-shaped specimen. Thus, the crack initiation occurs at the center of the specimen. Brazilian tensile strength (BTS) can be calculated from the following equation:

$$BTS = \frac{2P}{\pi Dt} = 0.636\frac{P}{Dt} \tag{1}$$

where P is the maximum load recorded during the test. D is the diameter and t is the thickness of specimen. This equation is derived from Muskhelishvili's equations that give stress distributions in a disc-shaped specimen diametrically compressed under a line load (Muskhelishvili 1963).

In this research, Brazilian test is performed on the prepared specimens at different 2α angles (i.e., 2α = 0°, 10°, 15°, 20°, 45°, and 60°). Ten specimens were tested at each 2α angle, so a total of 600 specimens were subjected to the Brazilian test. 2α angle, also called contact angle, is central angle against the arc of a circle whose radius is equal to the radius of the disc-shaped specimen (Fig. 5). In beginning of the test, this angle is related to jaw type. For example, for flat jaw 2α=0°. Six pairs of jaws for the Brazilian test with different 2α angles (i.e., 2α = 0°, 10°, 15°, 20°, 45°, and 60°) were designed and constructed for this research (Fig. 6).

3. Results

3.1 Mineralogical and petrographic properties

Mineralogical, petrographic and textural characteristics of the rock samples were investigated by thin section studies based on ISRM (2007) standard procedure. The investigated rocks are composed of coarse grain crystals except for the sample of KHL which has a fine grain texture. The geometry of grains composing the rocks are angular with equivalent dimensions except the samples of ARL, BJL, and NRM which are composed of extended crystals (Fig. 7). The rocks contain various minerals such as quartz, alkali feldspar, plagioclase, calcite, amphibole, etc. that they are common in all rock types namely sedimentary, metamorphic, and igneous rocks. Calcite is the main mineral in the sedimentary and metamorphic rocks namely the samples of KHL, ARL, BJL, NRM, and MHM. The amin minerals in the studied skarn is Amphibole, and in the igneous rocks are Quartz and Feldspar. The average modal abundance of minerals in the samples were determined by point counting method and the results are summarized in Table 2.

3.2 Physical properties

The average values of physical properties for the tested

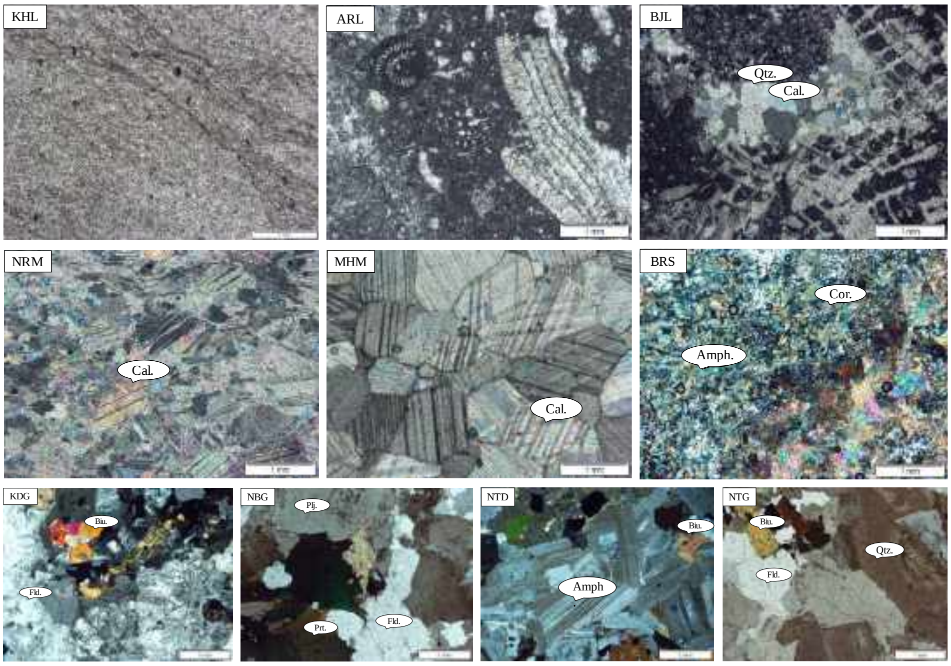

Fig. 7 Microscopic images of the rock samples in plane-polarized light Note: Qtz., Quartz; Fld., Alkali felspar; Plg., Plagioclase; Cal., Calcite; Bio., Biotite; Amph., Amphibole; Prt., Perlite; Cor., Chromite

Table 2 Type and mineral composition of the tested rock samples

Rock mark	Rock color	Rock name	Mineral content (%)										
			Qtz.	Fld.	Plg.	Cal.	Bio.	Amph.	Prt.	Epi.	Sfn.	Cor.	Other minerals
KHL	Light yellow to cream	Limestone	10	-	-	90	-	-	-	-	-	-	-
ARL	Cream to dark cream	Limestone	5	16	-	79	-	-	-	-	-	-	-
BJL	Pink	Limestone	12	10	-	75	3	-	-	-	-	-	-
NRM	White	Marble	-	-	-	96	-	-	-	-	-	-	4
MHM	Light gray	Marble	-	-	-	99	-	-	-	-	-	-	1
BRS	Dark green	Skarn	-	-	-	-	-	47	-	15	10	21	7
KDG	Cream to gray	Granite	13	35	10	-	12	14	-	10	-	-	6
NBG	Gray	Granite	20	27	15	-	3	-	34	-	-	-	1
NTD	Black	Diorite	15	-	38	-	12	24	-	5	-	-	6
NTG	Gray	Granodiorite	10	25	26	-	15	21	-	-	-	-	3

Note: Qtz., Quartz; Fld., Alkali felspar; Plg., Plagioclase; Cal., Calcite; Bio., Biotite; Amph., Amphibole; Prt., Perlite; Epi., Epidote; Sfn., Sphene; Cor., Chromite

Table 3 Physical properties of the tested rock samples

Rock mark	No. of tests	Value	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	n_e (%)	W_a (%)	G_s	Description of γ_d (Anon 1979)	Description of n_e (Anon 1979)
KHL	5	Min.	25.52	25.81	3.72	1.41	2.72	Moderate	Low
		Ave.	25.27	25.94	4.27	1.63	2.74		
		Max.	25.87	26.25	4.65	1.77	2.76		
		S.D.	0.13	0.18	0.35	0.13	0.01		
ARL	5	Min.	26.07	26.14	0.48	0.18	2.68	High	Very low
		Ave.	26.28	26.30	0.77	0.29	2.70		
		Max.	26.40	26.40	1.30	0.49	2.71		
		S.D.	0.12	0.10	0.31	0.11	0.01		

Table 3 Continued

Rock mark	No. of tests	Value	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	n_e (%)	W_a (%)	G_s	Description of γ_d (Anon 1979)	Description of n_e (Anon 1979)
BJL	5	Min.	25.95	26.00	0.50	0.19	2.66	High	Very low
		Ave.	26.06	26.08	0.56	0.21	2.67		
		Max.	26.15	26.15	0.72	0.27	2.68		
		S.D.	0.07	0.05	0.09	0.03	0.00		
NRM	5	Min.	26.18	26.20	0.14	0.05	2.67	High	Very low
		Ave.	26.29	26.30	0.15	0.06	2.68		
		Max.	26.49	26.51	0.21	0.08	2.70		
		S.D.	0.12	0.12	0.02	0.01	0.01		
MHM	5	Min.	24.03	24.07	0.19	0.07	2.46	Moderate	Very low
		Ave.	25.34	25.35	0.36	0.14	2.59		
		Max.	25.79	52.79	0.58	0.22	2.64		
		S.D.	0.73	0.72	0.16	0.06	0.07		
BRS	5	Min.	29.26	29.26	0.16	0.05	2.99	Very high	Very low
		Ave.	29.78	29.79	0.26	0.08	3.04		
		Max.	30.51	30.51	0.32	0.11	3.12		
		S.D.	0.47	0.46	0.06	0.02	0.04		
KDG	5	Min.	24.98	24.98	1.41	0.54	2.59	Moderate	Low
		Ave.	25.29	25.36	1.64	0.63	2.62		
		Max.	25.56	25.56	1.83	0.72	2.64		
		S.D.	0.20	0.23	0.18	0.07	0.01		
NBG	5	Min.	25.32	25.32	0.49	0.19	2.59	Moderate	Very low
		Ave.	25.42	25.44	0.59	0.23	2.61		
		Max.	25.47	25.51	0.64	0.25	2.61		
		S.D.	0.06	0.07	0.06	0.02	0.01		
NTD	5	Min.	27.35	27.39	0.34	0.12	2.80	Very high	Very low
		Ave.	27.86	27.87	0.53	0.19	2.85		
		Max.	28.48	28.48	0.85	0.30	2.92		
		S.D.	0.43	0.42	0.19	0.07	0.04		
NTG	5	Min.	25.76	25.76	0.60	0.23	2.65	High	Very low
		Ave.	26.11	26.14	0.72	0.27	2.68		
		Max.	26.94	27.01	0.90	0.34	2.77		
		S.D.	0.48	0.51	0.11	0.04	0.05		

Note: γ_d, dry unit weight; γ_s, saturated unit weight; n_e, effective porosity; W_a, water absorption; G_s, specific gravity; Min., minimum; Ave., Average; Max., maximum; S.D., standard deviation

Table 4 Values of Brazilian tensile strength of the tested rock samples at different 2α angles

Rock mark	2α angle (deg.)	No. of tests	BTS (MPa)			S.D.	CR (%)
			Min.	Ave.	Max.		
KHL	0 (Flat)	10	7.10	8.59	10.27	1.05	-
	10 (St.)	10	6.81	8.84	11.50	1.43	0.92
	15	10	8.13	12.11	15.92	2.32	12.26
	30	10	24.33	34.70	40.65	5.36	84.69
	45	10	26.29	41.96	58.99	11.98	27.21
	60	10	27.43	35.27	47.51	5.88	-25.07
ARL	0 (Flat)	10	4.61	5.98	7.34	1.01	-

Table 4 Continued

Rock mark	2α angle (deg.)	No. of tests	BTS (MPa)			S.D.	CR (%)
			Min.	Ave.	Max.		
ARL	10 (St.)	10	4.76	6.29	9.93	1.50	2.59
	15	10	8.02	10.52	12.80	1.79	35.48
	30	10	7.78	13.32	20.02	3.48	23.38
	45	10	6.19	15.67	22.20	4.68	19.70
	60	10	9.89	17.91	25.07	4.59	18.85
TBJL	0 (Flat)	10	4.39	5.64	6.77	0.87	-
	10 (St.)	10	5.88	7.49	9.13	1.06	11.72
	15	10	5.42	8.97	11.67	1.99	9.37
	30	10	11.01	14.01	18.03	2.86	32.00
	45	10	10.99	18.68	31.42	6.09	29.64
	60	10	13.89	21.40	28.76	5.32	17.27
NRM	0 (Flat)	10	4.84	7.14	8.66	1.12	-
	10 (St.)	10	5.79	7.68	9.70	1.14	6.03
	15	10	9.54	11.67	14.83	1.58	44.41
	30	10	9.48	13.97	16.18	2.09	25.50
	45	10	17.23	18.89	23.22	1.90	54.82
	60	10	12.17	16.13	21.13	2.81	-30.75
MHM	0 (Flat)	10	2.78	3.81	6.46	1.18	-
	10 (St.)	10	3.84	5.23	6.60	0.91	16.63
	15	10	3.58	6.60	9.21	1.90	16.04
	30	10	6.18	8.86	10.59	1.68	26.39
	45	10	8.67	12.00	14.32	1.83	36.76
	60	10	9.78	12.36	15.57	1.54	4.17
BRS	0 (Flat)	10	11.61	18.03	23.09	4.07	-
	10 (St.)	10	17.16	20.83	26.39	3.53	7.61
	15	10	18.32	22.35	27.74	3.52	4.15
	30	10	39.87	51.89	59.48	6.06	80.43
	45	10	37.38	53.34	69.05	9.26	3.94
	60	10	39.77	54.76	88.94	13.25	3.87
KDG	0 (Flat)	10	5.24	6.76	7.78	0.90	-
	10 (St.)	10	5.97	9.23	10.60	1.29	10.98
	15	10	6.90	10.09	12.09	1.61	3.86
	30	10	16.64	22.08	29.53	3.78	53.37
	45	10	30.85	34.61	40.63	3.10	55.83
	60	10	18.77	29.21	46.10	7.44	-24.04
NBG	0 (Flat)	10	6.84	9.36	12.31	1.81	-
	10 (St.)	10	8.88	11.38	12.94	1.27	7.07
	15	10	10.53	13.46	16.49	1.78	7.30
	30	10	21.67	27.26	34.03	3.93	48.40
	45	10	19.00	32.91	51.69	10.65	19.83
	60	10	23.06	37.87	49.94	9.01	17.40
NTD	0 (Flat)	10	7.37	12.78	18.37	3.24	-
	10 (St.)	10	8.22	13.51	17.61	2.75	2.86
	15	10	11.78	18.58	23.17	3.98	19.82

Table 4 Continued

Rock mark	2α angle (deg.)	No. of tests	BTS (MPa)			S.D.	CR (%)
			Min.	Ave.	Max.		
NTD	30	10	27.91	38.71	51.70	7.66	78.81
	45	10	34.94	44.39	70.18	10.96	22.21
	60	10	32.11	38.33	53.44	8.03	-23.69
NTG	0 (Flat)	10	5.50	8.25	11.92	1.84	-
	10 (St.)	10	8.57	11.78	16.05	2.15	10.06
	15	10	10.04	14.53	18.79	2.54	7.86
	30	10	18.21	30.25	37.28	6.25	44.87
	45	10	36.69	44.68	53.30	6.16	41.16
	60	10	35.88	43.30	52.09	5.31	-3.95

Note: BTS, Brazilian tensile strength; Min., minimum; Ave., Average; Max., maximum; S.D., standard deviation; CR, change ratio; St., standard

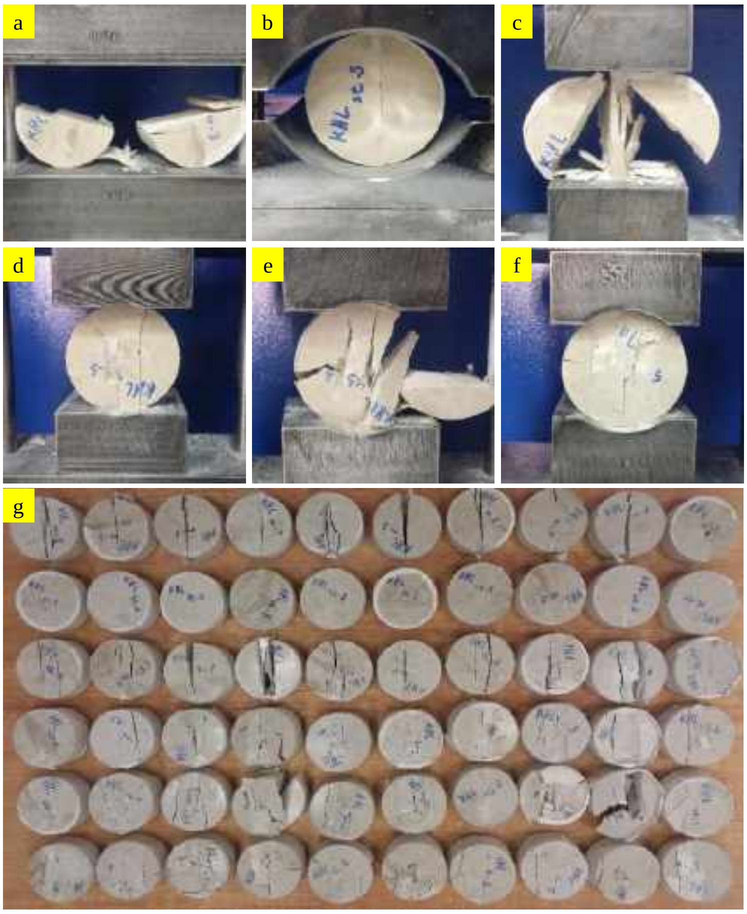

Fig. 8 Failure patterns of the sample of KHL under different 2α angles; (a) 2α=0° (flat jaw), (b) 2α=10° (standard jaw), (c) 2α=15°, (d) 2α=30°, (e) 2α=45°, (f) 2α=60° and (g) all specimens

rock samples are outlined in Table 3.

3.3 Brazilian tensile strength

Fig. 8 shows failure patterns of the sample of KHL in different 2α angles. In all states, the failure patterns are similar to each other; this means that tensile cracks are always created in vertical direction. The average values of BTS are listed in Table 4.

4. Discussions

In this research, mineralogical, petrographic and textural characteristics of the rock samples were investigated. It is found that nine samples of ten studied rocks are composed

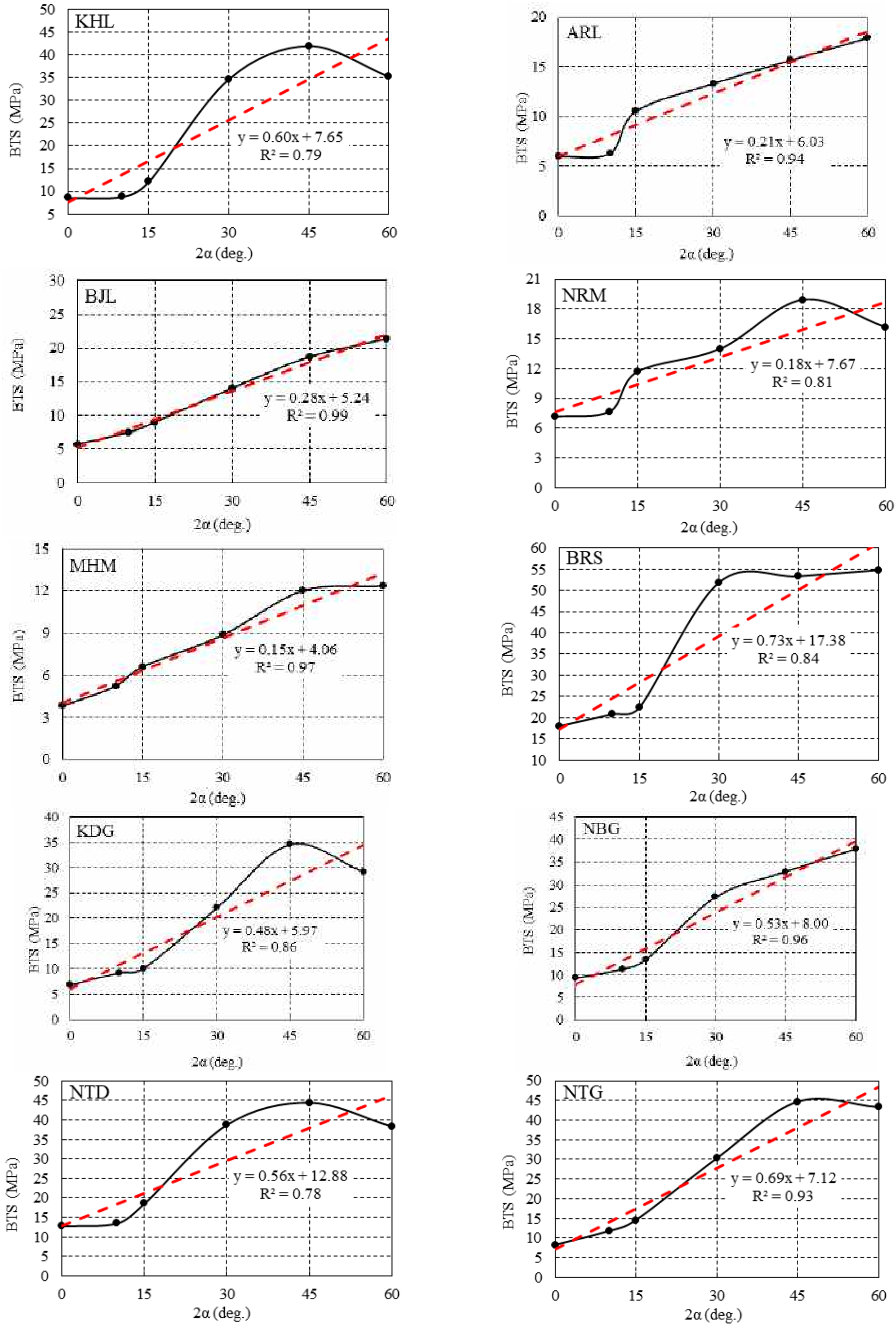

Fig. 9 Correlations between BTS and 2α angle for the tested rock samples

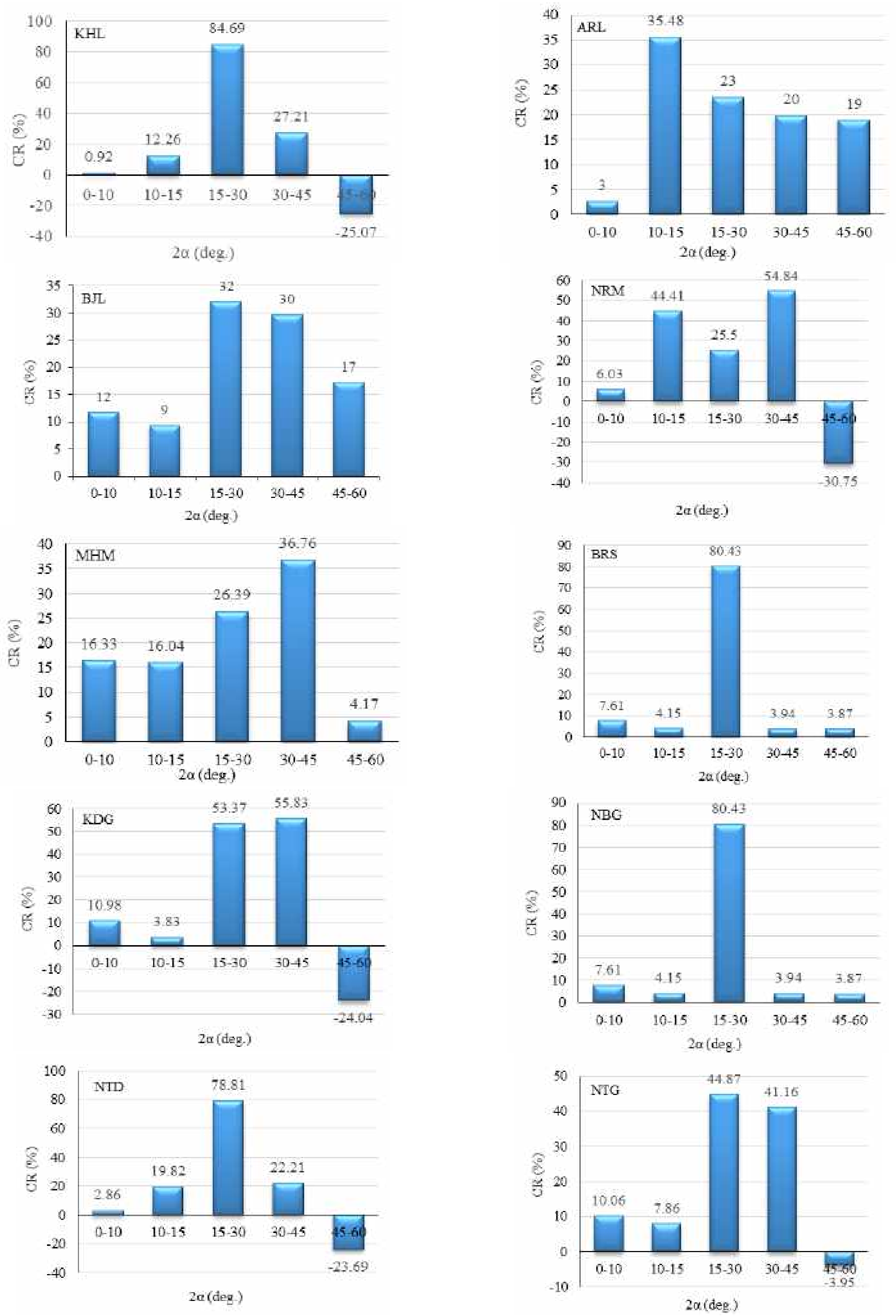

Fig. 10 Change ratio (CR) diagrams of Brazilian tensile strength with increasing 2α angle for the tested rock samples

of coarse grain crystals and only one rock has a fine grain texture which is the sample of KHL. The most important minerals composing the rocks are quartz, alkali feldspar, plagioclase, calcite, and amphibole which are common in all rock types. The studied rocks have moderate to very high dry unite weight and low to very low porosity based on Anon (1979) classification. Minimum and maximum values of dry unite weight were obtained for the samples of KHL and BRS equal to 25.27 and 29.78 kN/m^3, respectively. Minimum and maximum values of porosity are for the samples of NRM and KHL equal to 0.15 and 4.27%, respectively. These results were expected according to the cognitive that we had from the samples obtained from hand specimen observations and their behaviors during laboratory tests. These results are comparable with the results presented by Khanlari *et al.* (2014) and Fereidooni (2016).

Brazilian tensile strength for the tested rocks is obtained between 3.81 MPa at 2α=0° for the sample of MHM, and 54.76 MPa at 2α=60° for the sample of BRS. This range of values is logical and it is similar to the values presented in previous research works (i.e., Cai 2010, Mishra and Basu 2012, Perras and Diederichs 2014, Komurlu and Kesimal 2015, Markides and Kourkoulis 2016, Ma and Huang 2018).

When using standard jaw with 2α=10°, Brazilian tensile strength of the rocks is between 5.23 MPa at 2α=0° for the sample of MHM and 20.83 MPa at 2α=60° for the sample of BRS. As expected, this range is smaller than the range obtained at all contact angles (2α=0°−60°). Generally, the value of Brazilian tensile strength increases with increasing 2α angle from 0° to 60° for the studied rocks. According to the graphs presented in Fig. 9, the relationships between 2α angle and Brazilian tensile strength are direct linear with determination coefficient (R^2) between 0.78 and 0.99. This achievement is confirmed by the results presented in Komurlu and Kesimal (2015) and Markides and Kourkoulis (2016). The black curves show BTS changes between two consecutive values of 2α angle (for example, between 15° and 30°). These changes which may be positive or negative with different rates, are not distinguishable from the dashed lines. It is noteworthy that for five samples of the rocks, Brazilian tensile strength is decreased at 2α=60°. In other words, for five samples, Brazilian tensile strength is completely additive while, in the other five samples it is decreasing. There is not detected any specific reason such as origin, lithology, mineralogy or rock texture for decreasing the parameter at 2α=60°. Maybe it is related to test condition in the laboratory.

There is a parameter is proposed to investigate the rate of changes in Brazilian tensile strength of the rocks with increasing 2α angle. This parameter is called change ratio (CR) and it can be calculated from the following formula:

$$CR = \frac{BTS_n - BTS_{n-1}}{BTS_{\max} - BTS_{\min}} \times 100 \qquad (2)$$

where, BTS_n is Brazilian tensile strength at a certain 2α angle (for example 30°), BTS_n is Brazilian tensile strength at previous 2α angle (for instance 15°), BTS_{max} and BTS_{min} are maximum and minimum of Brazilian tensile strengths of the rock sample (the former is at 2α=45° or 60°, and the latter is at 2α=0°). The values of CR obtained from the above formula for the studied rocks are illustrated in Fig. 10. As can be seen, CR is low in 2α range between 0° and 10°. This indicates that the value of Brazilian tensile strength of the rocks tested by flat (2α=0°) and standard (2α=10°) jaws, which are suggested by ASTM (1996) and ISRM (2007), respectively, are near to each other. In fact, it does not matter which jaw (flat or standard) is used when we want to perform Brazilian test for a rock sample. Because, both jaws are suggested by the standards and provide close values for Brazilian tensile strength of the rock. Maximum value of CR in 2α range between 0° and 10° is obtained for the sample of MHM equal to 16.33%, and CR is less than 10% in most samples in this range.

Maximum value of CR for one sample of ten studied rocks is in range of 2α=10°−15°, for six samples is in range of 2α=15°−30°, and for three samples is in range of 2α=30°−45°. Therefore, CR in range of 2α=15°−30° has maximum value for most studied rocks. In 2α range between 45° and 60°, the value of CR decreases even; it has negative value in five samples. This means that Brazilian tensile strength decreases in this range for these samples. There is not exist any clear relation between CR rate from one side and lithology, mineral content, crystal size, density, and porosity of the rocks from other side. Since the CR has not been presented in previous research works, finding any possible relation between the parameters needs to test more rocks from various types, mineral contents, crystal sizes, densities, and porosities as well as a good data analyzing. In any case, this is clear that in some samples the value of CR is negative in 2α=45°−60°.

5. Conclusions

• The tested rocks are composed of various common minerals such as quartz, alkali feldspar, plagioclase, calcite, amphibole, etc. often with coarse-grained texture.

• These rocks are moderate to very high in dry unite weight and low to very low in porosity according to Anon (1979).

• Brazilian tensile strength is determined for the rocks at different contact angles by using the built steel jaws for this purpose. Overall, the parameter is between 3.81 MPa at 2α=0° for the sample of MHM, and 54.76 MPa at 2α=60° for the sample of BRS.

• The value of Brazilian tensile strength increases with increasing 2α angle up to 60°. For five samples of the rocks, Brazilian tensile strength is only decreased at 2α = 60°.

• The relationships between 2α angle and Brazilian tensile strength of the rocks are direct linear with very good determination coefficient (R^2).

• A parameter namely change ratio (CR) is proposed to investigate the rate of changes in Brazilian tensile strength of the rocks between two consecutive values of 2α angle (for example, between 15° and 30°). These changes may be positive or negative with different rates.

• There is not exist any clear relation between CR rate and mineral content or texture of the rocks.

• By using standard jaw with 2α=10°, Brazilian tensile strength of the rocks is between 5.23 and 20.83 MPa.

Acknowledgments

The authors acknowledge the official supports of the Engineering Geology and Rock Mechanics Laboratory of Damghan University for performing all laboratory tests of the research.

References

Aliabadian, Z., Zhao, G.F. and Russell, A.R. (2019), "Failure, crack initiation and the tensile strength of transversely isotropic rock using the Brazilian test", *Int. J. Rock Mech. Min. Sci.*, **122**, 104073. https://doi.org/10.1016/j.ijrmms.2019.104073.

Anon, O. (1979), "Classification of rocks and soils for engineering geological mapping. Part 1: Rock and soil materials", *Bull. Int. Assoc. Eng. Geol.*, **19**, 355-371.

Aonoa, Y., Tani, K., Okada, T. and Sakai, M. (2012). "Failure mechanism of the specimen in the splitting tensile strength test", *Proceedings of the ISRM Regional Symposium-7th Asian Rock Mechanics Symposium*, Seoul, Korea, October.

ASTM (2008), *Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens*, in *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Barla, G. and Innaurato, N. (1973), "Indirect tensile testing of anisotropic rocks", *Rock Mech.*, **5**(4), 215-230. https://doi.org/10.1007/BF01301795.

Briševac, Z., Kujundžić, T. and Čajić, S. (2015), "Current cognition of rock tensile strength testing by Brazilian test", *Rudarsko-geološko-naftni zbornik*, **30**(2), 101-114. https://doi.org/10.17794/rgn.2015.2.2.

Burkhardt, M., Kim, E. and Nelson, P.P. (2018), "EMI database analysis focusing on relationship between density and mechanical properties of sedimentary rocks", *Geomech. Eng.*, **14**(5), 491-498. https://doi.org/10.12989/gae.2018.14.5.491.

Cai, M. (2010), "Practical estimates of tensile strength and the Hoek-Brown strength parameter mi of brittle rocks", *Rock Mech. Rock Eng.*, **43**(2), 167-184. https://doi.org/10.1007/s00603-009-0053-1.

Carneiro, F. (1943), "A new method to determine the tensile strength of concrete", *Proceedings of the 5th Meeting of the Brazilian Association for Technical Rules*, Sao Paulo, Brazil.

Dan, D.Q., Konietzky, H. and Herbst, M. (2013), "Brazilian tensile strength tests on some anisotropic rocks", *Int. J. Rock Mech. Min. Sci.*, **58**, 1-7. https://doi.org/10.1016/j.ijrmms.2012.08.010.

Erarslan, N. and Williams, D.J. (2012), "Experimental, numerical and analytical studies on tensile strength of rocks", *Int. J. Rock Mech. Min. Sci.*, **49**, 21-30. https://doi.org/10.1016/j.ijrmms.2011.11.007.

Fairhurst, C. (1964), "On the validity of the 'Brazilian'test for brittle materials", *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, **1**(4), 535-546. https://doi.org/10.1016/0148-9062(64)90060-9.

Fereidooni, D. (2016), "Determination of the geotechnical characteristics of hornfelsic rocks with a particular emphasis on the correlation between physical and mechanical properties", *Rock Mech. Rock Eng.*, **49**(7), 2595-2608. https://doi.org/10.1007/s00603-016-0930-3.

García, V.J., Márquez, C.O., Zúñiga-Suárez, A.R., Zuñiga-Torres, B.C. and Villalta-Granda, L.J. (2017), "Brazilian test of concrete specimens subjected to different loading geometries: Review and new insights", *Int. J. Concrete Struct. Mater.*, **11**(2), 343-363. https://doi.org/10.1007/s40069-017-0194-7.

Hondros, G. (1959), "The evaluation of Poisson's ratio and the modulus of materials of low tensile resistance by the Brazilian (indirect tensile) test with particular reference to concrete", *Australian J. Appl. Sci.*, **10**(3), 243-268.

Huang, Y.H., Yang, S.Q. and Zhang, C.S. (2017), "Strength failure behavior of granite containing two holes under Brazilian test", *Geomech. Eng.*, **12**(6), 919-933. https://doi.org/10.12989/gae.2017.12.6.919.

ISRM (1977), *Suggested Methods for Determining Tensile Strength of Rock Materials*, Commission on Standardization of Laboratory Field Tests, Committee on Laboratory Tests.

ISRM (2007), *The Blue Book–The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974–2006*, Compilation Arranged by the ISRM Turkish National Group, Kazan Offset Press, Ankara, Turkey.

Istvan, J., Evans, L., Weber, J. and Devine, C. (1997), "Rock mechanics for gas storage in bedded salt caverns", *Int. J. Rock Mech. Min. Sci.*, **34**(3-4), 142. https://doi.org/10.1016/S1365-1609(97)00108-1.

Jaeger, J.C., Cook, N.G. and Zimmerman, R. (2009), *Fundamentals of Rock Mechanics*, John Wiley & Sons.

Khanlari, G.R., Heidari, M., Sepahigero, A.A. and Fereidooni, D. (2014), "Quantification of strength anisotropy of metamorphic rocks of the Hamedan province, Iran, as determined from cylindrical punch, point load and Brazilian tests", *Eng. Geol.*, **169**, 80-90. https://doi.org/10.1016/j.enggeo.2013.11.014.

Khanlari, G.R., Heidari, M., Sepahi-Gero, A.A. and Fereidooni, D. (2014), "Determination of geotechnical properties of anisotropic rocks using some index tests", *Geotech. Test. J.*, **37**(2), 242-254. https://doi.org/10.1520/GTJ20130078.

Komurlu, E. and Kesimal, A. (2015), "Evaluation of indirect tensile strength of rocks using different types of jaws", *Rock Mech. Rock Eng.*, **48**(4), 1723-1730. https://doi.org/10.1007/s00603-014-0644-3.

Kourkoulis, S., Markides, C.F. and Chatzistergos, P. (2013a), "The standardized Brazilian disc test as a contact problem", *Int. J. Rock Mech. Min. Sci.*, **57**, 132-141. https://doi.org/10.1016/j.ijrmms.2012.07.016.

Kourkoulis, S., Markides, C.F. and Hemsley, J. (2013b), "Frictional stresses at the disc–jaw interface during the standardized execution of the Brazilian disc test", *Acta Mechanica*, **224**(2), 255-268. https://doi.org/10.1007/s00707-012-0756-3.

Lanaro, F., Sato, T. and Stephansson, O. (2009), "Microcrack modelling of Brazilian tensile tests with the boundary element method", *Int. J. Rock Mech. Min. Sci.*, **46**(3), 450-461. https://doi.org/10.1016/j.ijrmms.2008.11.007.

Li, D. and Wong, L.N.Y. (2013), "The Brazilian disc test for rock mechanics applications: Review and new insights", *Rock Mech. Rock Eng.*, **46**(2), 269-287. https://doi.org/10.1007/s00603-012-0257-7.

Ma, Y. and Huang, H. (2018), "DEM analysis of failure mechanisms in the intact Brazilian test", *Int. J. Rock Mech. Min. Sci.*, **102**, 109-119. https://doi.org/10.1016/j.ijrmms.2017.11.010.

Markides, C.F. and Kourkoulis, S. (2016), "The influence of jaw's curvature on the results of the Brazilian disc test", *J. Rock Mech. Geotech. Eng.*, **8**(2), 127-146. https://doi.org/10.1016/j.jrmge.2015.09.008.

Markides, C.F., Pazis, D. and Kourkoulis, S. (2010), "Closed full-field solutions for stresses and displacements in the Brazilian disk under distributed radial load", *Int. J. Rock Mech. Min. Sci.*, **47**(2), 227-237. https://doi.org/10.1016/j.ijrmms.2009.11.006.

Markides, C.F., Pazis, D. and Kourkoulis, S. (2012), "The Brazilian disc under non-uniform distribution of radial pressure and friction", *Int. J. Rock Mech. Min. Sci.*, **50**, 47-55.

https://doi.org/10.1016/j.ijrmms.2011.12.012.
Mellor, M. and Hawkes, I. (1971), "Measurement of tensile strength by diametral compression of discs and annuli", *Eng. Geol.*, **5**(3), 173-225. https://doi.org/10.1016/0013-7952(71)90001-9.
Mishra, D.A. and Basu, A. (2012), "Use of the block punch test to predict the compressive and tensile strengths of rocks", *Int. J. Rock Mech. Min. Sci.*, **51**, 119-127. https://doi.org/10.1016/j.ijrmms.2012.01.016.
Muskhelishvili, N. (1963), *Some Basic Problems of the Mathematical Theory of Elasticity*, Noordhoff, Groningen, The Netherlands.
Perras, M.A. and Diederichs, M.S. (2014), "A review of the tensile strength of rock: Concepts and testing", *Geotech. Geol. Eng.*, **32**(2), 525-546. https://doi.org/10.1007/s10706-014-9732-0.
Rocco, C., Guinea, G., Planas, J. and Elices, M. (2001), "Review of the splitting-test standards from a fracture mechanics point of view", *Cement Concrete Res.*, **31**(1), 73-82. https://doi.org/10.1016/S0008-8846(00)00425-7.
Seto, M., Nag, D.K., Vutukuri, V. and Katsuyama, K. (1997), "Effect of chemical additives on the strength of sandstone", *Int. J. Rock Mech. Min. Sci.*, **34**(3-4), 280. https://doi.org/10.1016/S1365-1609(97)00283-9.
Tan, X., Konietzky, H., Frühwirt, T. and Dan, D.Q. (2015), "Brazilian tests on transversely isotropic rocks: Laboratory testing and numerical simulations", *Rock Mech. Rock Eng.*, **48**(4), 1341-1351. https://doi.org/10.1007/s00603-014-0629-2.
Tutmez, B. (2017), "Comparison of measurement uncertainty calculation methods on example of indirect tensile strength measurement", *Geomech. Eng.*, **12**(6), 871-882. https://doi.org/10.12989/gae.2017.12.6.871.
Wei, J., Niu, L., Song, J.J. and Xie, L. (2019), "Estimation of rock tensile and compressive moduli with Brazilian disc test", *Geomech. Eng.*, **19**(4), 353-360. https://doi.org/10.12989/gae.2019.19.4.353.
Yousefi, H. (2019), "Investigating the influence of effective parameters on Brazilian tensile strength of rocks with emphasis on jaw arch central angle of the test", M.Sc. Thesis, Damghan University, Damghan, Iran.

CC