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Full Length Article

Introducing a new rock abrasivity index using a scaled down disc cutter

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ABSTRACT

Rock abrasivity influences wear of cutting tools and consequently, performance of mechanized tunneling machines. Several methods have been proposed to evaluate rock abrasivity in recent decades, each one has its own advantages. In this paper, a new method is introduced to estimate wear of disc cutters based on rock cutting tests using scaled down discs (i.e. 54 and 72 mm diameter). The discs are made of H13 steel, which is a common steel type in producing real-scale discs, with hardness of 32 and 54 HRC. The small-scale linear rock cutting machine and a new abrasion test apparatus, namely University of Tehran abrasivity test machine, are utilized to perform the tests. Tip width of the worn discs is monitored and presented as the function of the accumulated test run to classify the rock abrasion. Abrasivity tests show that by increasing the uniaxial compressive strength (UCS) of the rock samples, wear rate is doubled gradually that reveals the sensitivity of the test procedure to the main parameters affecting the abrasivity of hard rocks. For the rocks with the highest UCS, the normal wear stops after performing 5 to 10 rounds of the tests, and then, deformation of the disc tip is detectable. Two abrasivity indices are defined based on the abrasivity tests results and their correlations with Cerchar Abrasivity Index (CAI) and UCS are established. Comparison of the established correlations in this study with previous investigations demonstrates the sensitivity of the indices to the parameters affecting wear of the disc cutters and repeatability of the outputs obtained from abrasivity tests using scaled down discs. Findings of this study can be used to enhance the accuracy of rock abrasivity classifications.

1. Introduction

TBM tunneling has several advantages compared to conventional methods in hard rocks and soft grounds. Some of those privileges are the higher safety, operating in different geological conditions, higher advance rate, less disturbance of the surrounding ground, and smooth walls of the tunnel perimeter (Maidl et al., 2008). Despite the numerous benefits of the mechanized tunneling, some factors including wear of the cutting tools have adverse impact on the feasibility of this method, mainly in hard rocks. Therefore, one of the great challenges in hard rock mechanized tunneling is the wear assessment of the cutting tool, especially disc cutters (Bruland, 1998). The accuracy of the wear prediction models directly affects the costs and duration of tunneling projects.

To address the need for the wear estimation models and in the absence of a standard testing procedure, several methods have been introduced and utilized for wear evaluation (Gehring, 1995). Table 1 provides a list of the five common testing methods of estimating the abrasion of materials and Fig. 1 presents an illustration for these methods. Some of these methods present a qualitative assessment of the hardness and abrasion of the materials, like the Mohs hardness scale (Paez, 2014), while others provide a quantitative evaluation, such as Cerchar abrasivity test (Alber et al., 2013).

Among the testing methods mentioned in Table 1 that provide a quantitative estimation of wear, Cerchar and NTNU have some specific strength. For instance, Cerchar abrasivity test has become one of the most common tests because of the simplicity of its procedure, low cost, fast preparation of the rock samples, and being susceptible to the main parameters affecting wear including uniaxial compressive strength (UCS) and equivalent quartz content (EQC), as noted by Rostami et al. (2014). NTNU test, evaluates the abrasion of the materials based on hardness and resistance of the rock powder particles (Dahl et al., 2012). This method has a big database and offers a chart to predict the cutter life, which makes the process of estimating the cutter life much faster and easier (Dahl et al., 2012).

However, conventional abrasivity tests listed in Table 1 have some shortcomings as follows. Despite the worldwide use of Cerchar test, the results for the same rock samples may vary significantly. This can be due

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Abbreviations and their definitions used in this study

Abbreviation	*Definition*
AV	Abrasion Value
AVS	Abrasion Value Cutter Steel
CAI	Cerchar Abrasivity Index
CCS	Constant Cross Section
d_u	Ultimate tip width
d_f	First round tip width
DWI	Disc Wear Index
EQC	Equivalent Quartz Content
h	Indentation depth in Rockwell hardness test
HRC	Hardness Rockwell C
HRB	Hardness Rockwell B
LAC	LCPC Abrasivity Coefficient
LCPC	Laboratoire Central Des Ponts Et Chausées
M	Mass
m	Mass
MEL-TMU	Mechanized Excavation Laboratory of Tarbiat Modares University
NAT	New Abrasion Test
NTNU	Norwegian University of Science and Technology
rpm	round per minute
RIAT	Rolling Indentation Abrasion Test
R–P	Roxborough And Phillips
Scwl	Specific cutter weight loss
SSLCM	Small-Scale Linear Cutting Machine
TBM	Tunnel Boring Machine
UAI	Ultimate Abrasivity Index
UCS	Uniaxial Compressive Strength
UTAI	University of Tehran Abrasivity Index
UTAT	University of Tehran Abrasivity Test
$V_{rolling}$	Rolling velocity
W	Wear Weight

Table 1
Most common rock abrasivity tests.

Test	Procedure	Wear criterion	Correlations	Reference
Cerchar	Scratching the material by a 55 HRC conical pin with 70 N normal force for 10 mm length	Tip width (mm) of the worn conical pin known as the Cerchar Abrasivity Index (CAI)	CAI = 10 d	Alber et al. (2013)
NTNU	Pushing the test piece on the rock powder (size <1 mm) with 10 kg normal dead load for 1–5 min	Weight loss (mg) of the Tungsten or steel test piece known as Abrasion value (AV) or Abrasion Value cutter steel (AVS)	AV or AVS = $M_{After} - M_{Before}$	Dahl et al. (2012)
LCPC	Rotation of a 60–75 HRB rectangular steel impeller for 5 min with 4500 rpm rotational speed in a container full of the material powder	Mass loss (g) of the impeller divided by the mass of the sample material (ton) known as LCPC Abrasivity Coefficient (LAC)	LAC = $(m_{after} - m_{before})/M_{material}$	Thuro et al. (2007)
Rockwell hardness	Indentation of a particular indenter into the material	Difference of the indentation depth (mm) at two specific times during the test known as Rockwell C Hardness (HRC)	HRC = 100 – (h/0.002)	Broz et al. (2006)
Moh's hardness scale	Scratching the material surface by the specified hardness minerals	Detectable trace of the groove on the softer material	A table of comparative hardness scale of ten selected minerals from Talc to Diamond	Tabor (1954)

to several reasons including the absence of a unique standard test procedure, the type of the device used for the test, pin hardness, roughness of the surface of the rock sample, and the method used to measure the tip width of the pin (Rostami et al., 2014). As NTNU test has shown different results for the same samples that were tested in different laboratories, it is recommended to perform the tests at SINTEF laboratory in order to obtain valid results (Farrokh and Kim, 2018).

LCPC test has smaller database compared to Cerchar and NTNU and also the validity of its results to be used in estimating the disc cutter wear is along with uncertainties because of the wear mechanism happens during the test as a result of very fast rotation of the propeller (Farrokh and Kim, 2018). Assessment of the wear of cutting tools by Rockwell hardness scale has some deficiencies such as small database and not being sensitive to the main parameters affecting the wear. Mohs hardness scale is also so simple, qualitative, and unable to present an accurate estimation of abrasion.

Beside these deficiencies in conventional abrasivity tests, the design of none of the aforementioned tests is capable enough to investigate the effect of all aspects of a tribology system. The tribology system of the rock cutting process consists of the mechanical behavior of the rock and the disc cutter, and the interaction properties between these two (Hamzaban et al., 2013). In the most common abrasivity tests, either just the mechanical properties of the rock is studied (e.g. Moh's and Rockwell hardness scales), or the mechanical behavior of the rock and the disc cutter is investigated (e.g. Cerchar and NTNU tests), but the influence of the interaction between the disc and rock is ignored. This interaction is defined as the rolling and indentation mechanism of the rock cutting process and plays an important role in wear evaluation.

In recent years, in order to include the effect of rolling and indentation mechanism on wear, researchers have introduced several tests which utilize scaled down disc cutters (Farrokh and Kim, 2018; Macias et al., 2016; Sun et al., 2019; Zhang et al., 2018). Some recently developed abrasivity tests are listed in Table 2 and illustrated in Fig. 2. The main advantage of the recently developed abrasivity tests, which was completely disregarded in the conventional tests, is their capability to model the rolling contact between the rock and the disc cutter. Apart from using disc cutters, some features make them equally feasible tests as conventional approaches. These include using intact rock, requiring small sample preparation, and utilizing small to medium-sized rock samples.

Development of the numerical simulations has motivated researchers to present a model of estimating wear using finite element and distinct element methods (Galeshi et al., 2020; Xue et al., 2020). Although using the numerical simulations provides a fast and economical estimation, experimental approach is believed to be more realistic and acceptable all over the world.

In this study, a new method, namely University of Tehran abrasivity test (UTAT), is introduced to evaluate rock abrasivity using a scaled down V-shaped disc cutter. The method is originally designed to cover the main drawback of the conventional methods which is ignoring the rolling – indentation mechanism of the rock cutting process. In this way, the V-shaped disc penetrates the rock in a preset penetration depth and has its own free rolling motion while moves forward to cut the surface of the rock. Since this disc cutter is constructed from the same type of steel with

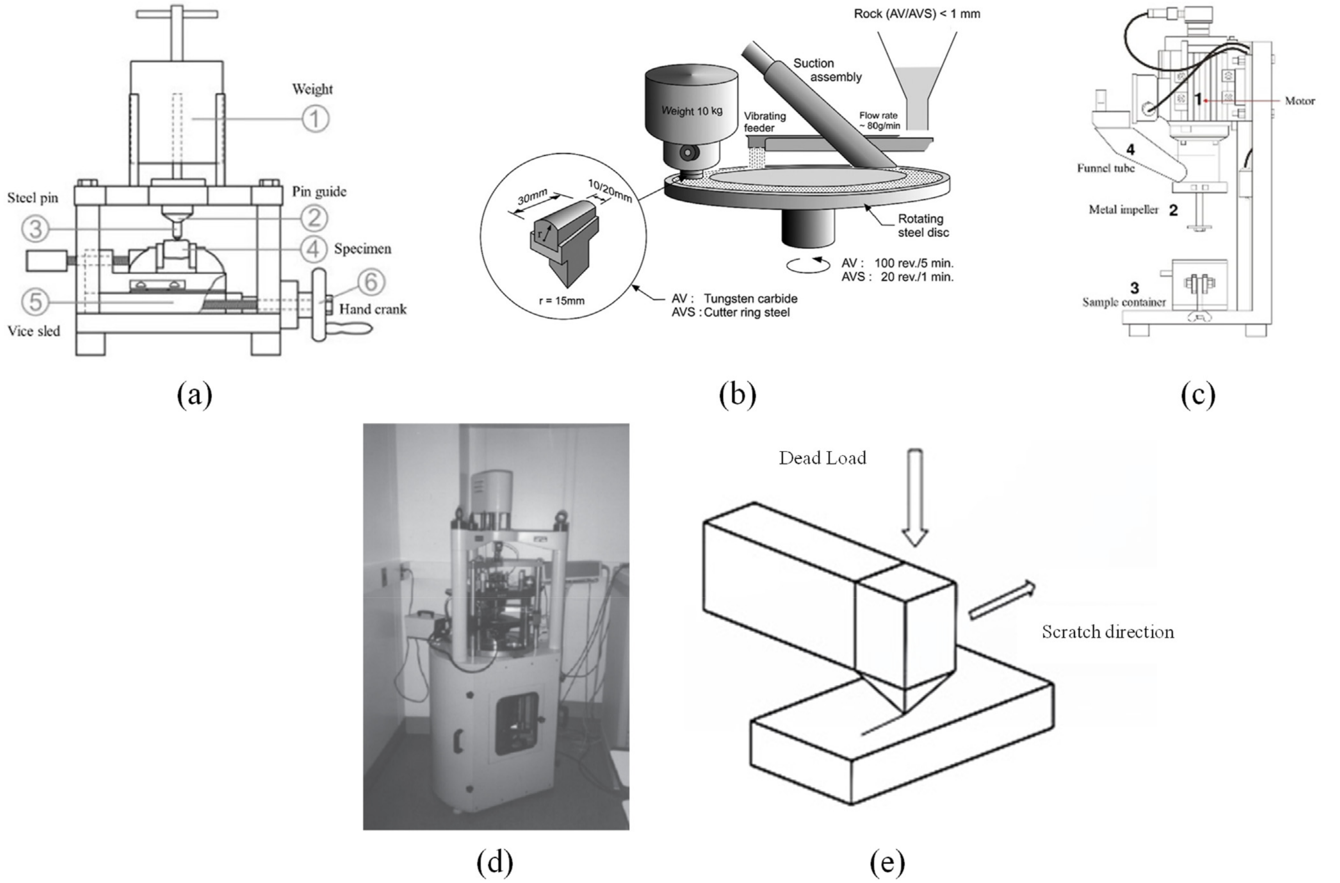

Fig. 1. The most common abrasion tests (a) Cerchar (Alber et al., 2013) (b) NTNU (Dahl et al., 2012) (c) LCPC (Thuro et al., 2007) (d) Rockwell hardness test (Broz et al., 2006) (e) Mohs hardness test (Tabor, 1954).

Table 2
Recently developed abrasivity tests using scaled down disc cutters.

Test	Disc features	Disc motion	Disc wear criterion	Correlations	Reference
Composite wear	Hardness 58 HRC Diameter 43.2 mm Thickness 1.9 mm	Penetration 5 mm Distance 100 m	Weight loss (mg) per 100 m of cutting test	$W = 0.7845\ CAI^{2}$	Sun et al. (2019)
Central South University of China	Hardness 55-58 HRC Diameter 140 mm Thickness 5 mm	Penetration 1 mm Distance 800 mm $V_{rolling}$ 20 rpm	Weight loss (g)	Graphs of the effect of different disc hardness values on weight loss of the disc	Zhang et al. (2018)
New Abrasion Test (NAT)	Hardness 56 HRC Diameter 47 mm Thickness 2 mm	Normal load 25 kg Distance 7.5 m	Specific cutter weight loss (mg/m)	$Scwl = 6.7018\ DWI^{0.43}$	Farrokh and Kim (2018)
Rolling Indentation Abrasion Test (RIAT)	Hardness 50 HRC Diameter 30 mm Thickness 4 mm	Normal load 1250 N $V_{Rolling}$ 40 rpm	Weight loss (mg)	$RIAT_a = 2.76\ CAI^{1.93}$ $RIAT_a = 4.19 \exp(0.07\ AVS)$ $RIAT_a = 2.46 \exp(3.81\ EQC)$	Macias et al. (2016)

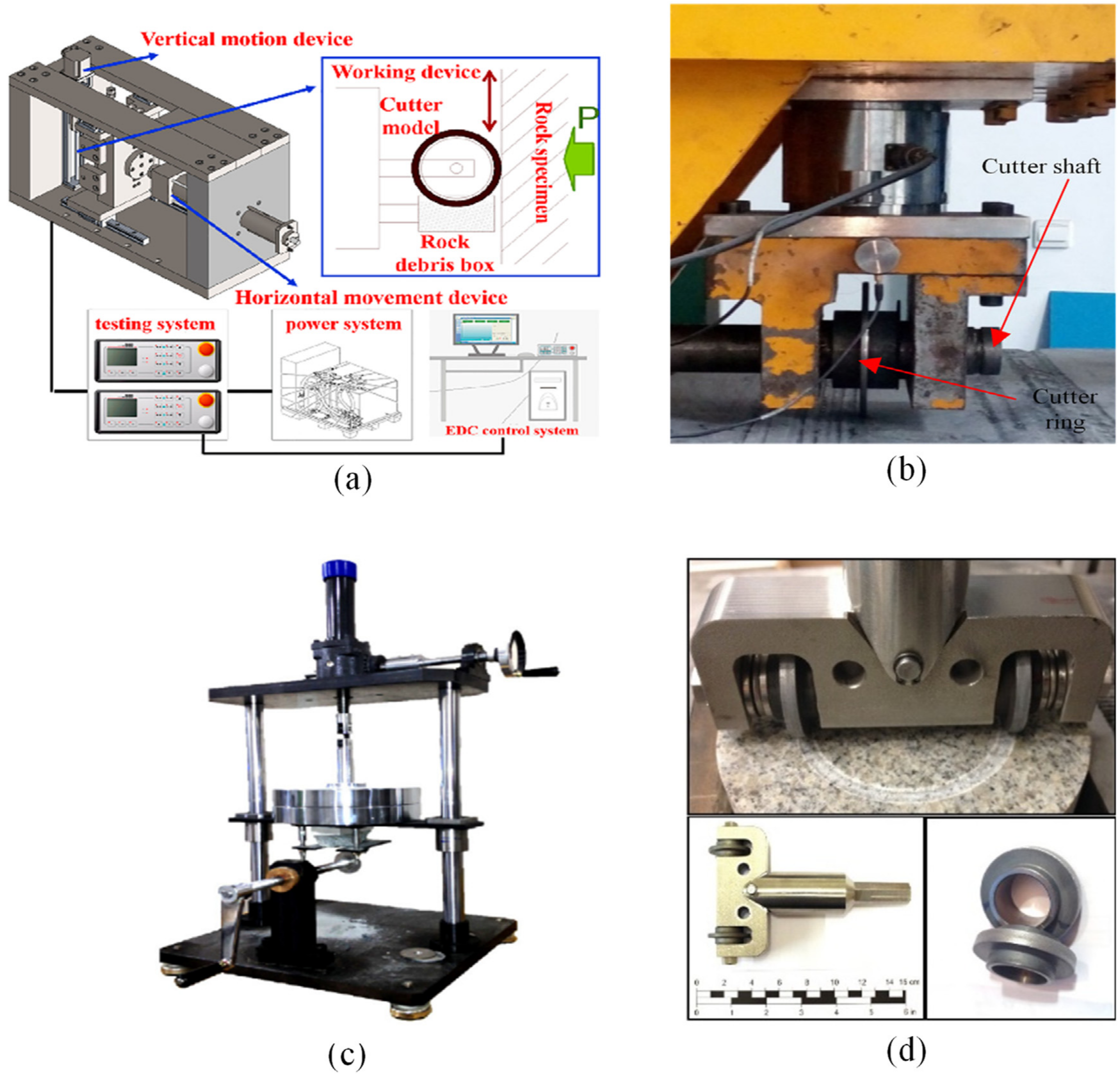

Fig. 2. Recently developed abrasion tests (a) Composite wear (Sun et al., 2019) (b) Central South University of China abrasivity (Zhang et al., 2018) (c) New abrasion (Farrokh and Kim, 2018) (d) RIAT (Macias et al., 2016).

equivalent hardness as the actual-scale disc cutters used in TBM tunneling projects, the proposed method constitutes a full tribology system.

This system mirrors the mechanical characteristics of both the rock and the cutting tool, as well as their rolling-indentation interaction mechanism. A notable feature of this method is the free rolling movement of the disc during the cutting operation, which facilitates a smooth and uniform wear of the disc tip. Additionally, by limiting the penetration depth, the likelihood of tip damage is significantly reduced, allowing for focused examination solely on normal wear patterns. Furthermore, by adopting conventional monitoring techniques to this test by measuring the tip width, normal wear is differentiated from deformation of the disc. This is an important advantage of the monitoring method of this study compared to recently developed abrasivity tests, mentioned in Tables 2 and in which the weight loss of the discs represents the wear and is unable to detect deformation of the tip. The V-shaped design of the discs enables them to penetrate the surface of rocks with lower force requirements compared to discs with constant cross sections. This design feature allows for the utilization of testing equipment with lower loading capacities, which are widely accessible globally. To enhance the applicability of the abrasivity test outputs, two abrasivity indices are introduced. These indices represent the wear as the function of the accumulated test run, which makes it possible to classify the abrasion of different rocks.

2. Techniques and facilities

The abrasivity test procedure consists of two steps. First, rock cutting test by a small-scale linear cutting machine for one round, i.e. cutting length equal to the perimeter of the discs (Section 2.1). At this point, the tip width of the worn disc is measured using a binocular (Section 2.4). Second, the rock cutting test continues for a longer cutting length on the worn disc using UTAT machine (Section 2.2). The tip width is measured sequentially by the binocular after one or several rounds of the cutting tests. The final cutting length is varied depending on the trend of the measured wear. All tests are performed at normal room temperature of 20 °C. The abovementioned devices are introduced in the following.

2.1. Linear cutting machine

The small-scale linear cutting machine (SSLCM) at Mechanized Excavation Laboratory of Tarbiat Modares University (MEL-TMU) was used for the first round of all abrasivity tests. In other words, SSLCM was

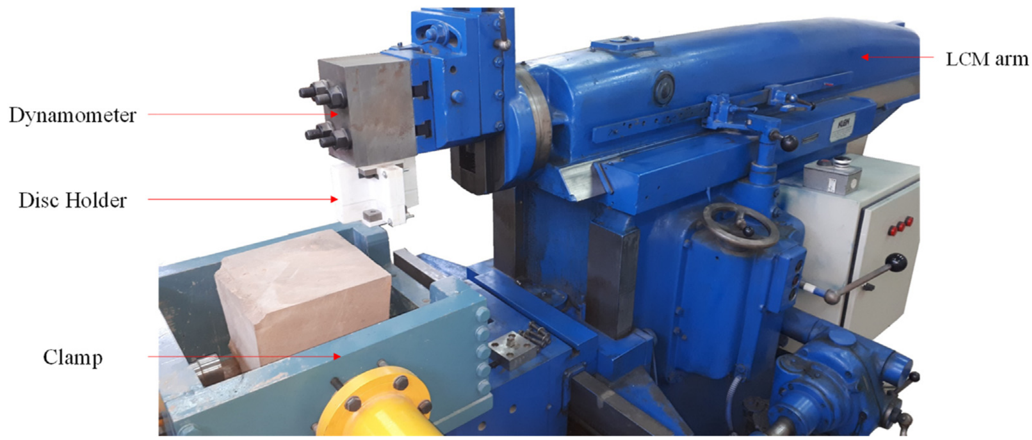

Fig. 3. Small-scale linear cutting machine in MEL-TMU.

utilized to perform the rock cutting tests using the sharp discs in a distance equal to their perimeter, which is 170 and 226 mm straight line of cut for the 54 and 72 mm discs, respectively. Fig. 3 shows the SSLCM which is incorporated for this study. This device consists of a modified hydraulic shaping machine with 5.9 kW power and maximum ram stroke of 900 mm, dynamometer, cutting tool and rock sample holders, and a data acquisition system (Mohammadi et al., 2020). Since its development, SSLCM has been fitted with three common rock cutting tools including chisels, conical picks, and mini-discs (Rostami et al., 2020; Mohammadi, 2020; Atarian, 2020; Izadshenass jahromi, 2019) Cutting velocity and depth are adjustable but they are fixed on 5 cm/s and 1 mm for all tests. Since this device is capable of monitoring forces in three directions, it is possible to validate the resulted forces with the theoretical model of Roxborough and Phillips (1975).

2.2. University of Tehran abrasivity test machine

After performing the first round of rock cutting, the tip width of the discs were measured by a binocular (section 2.4). Then, the second round is done using a new small-scale abrasivity test device developed at Rock Mechanics Laboratory of University of Tehran, namely UTAT machine. This device consists of a steel frame, disc holder, and a clamp (Fig. 4). Penetration depth is adjustable using a screw rod attached to the disc holder while the spacing of the cuts is set by positioning the rock sample holder. Regarding the results of the first and second rounds of the abrasivity tests, the cutting distance of the third to final round of tests are determined and the tip width is measured after the specified cutting distance. Cutting traces by the 54 mm disc with 80° tip angle on a Basalt sample is shown in Fig. 5. The idea of using a scaled down disc cutter in UTAT machine, which is a modified Cerchar apparatus, comes from the similar process that was previously utilized in SSLCM and rock cutting tests with miniature discs (i.e. 1–2 inches in diameter).

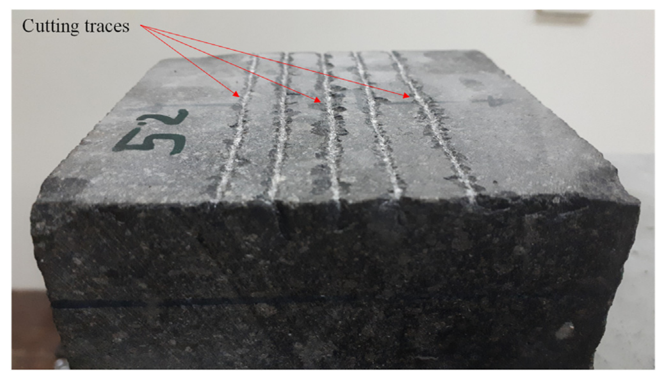

Fig. 5. Cutting traces on a basalt sample.

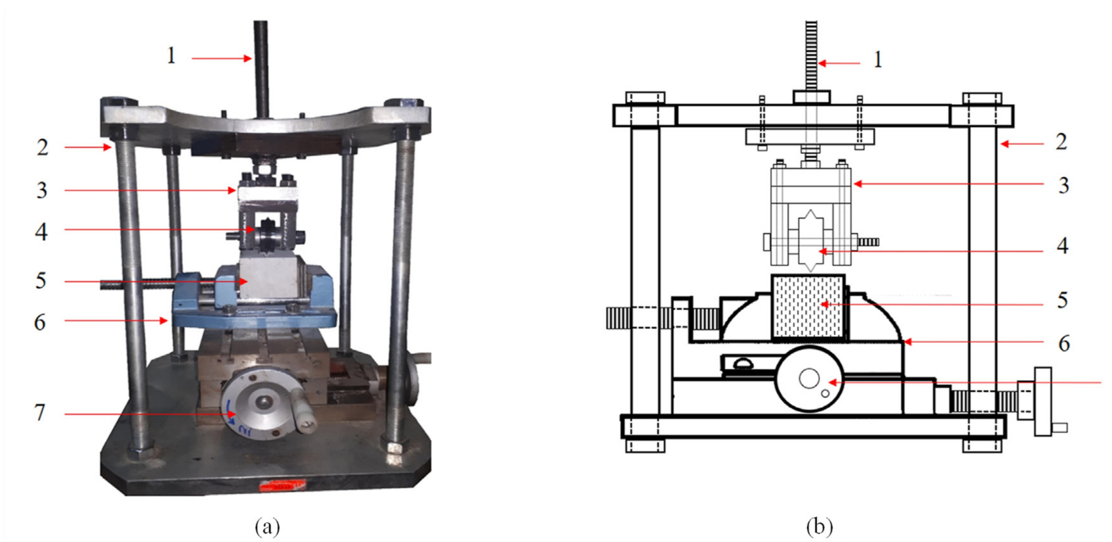

Fig. 4. UTAT machine (a) 3D view (b) schematic view (1) Screw rod (2) Steel frame (3) Disc holder (4) Disc (5) Rock sample (6) Clamp (7) Pulley.

2.3. Scaled down disc cutters

Disc cutters are categorized into the V-shaped and the CCS ones based on the cross section shape of the ring. Nowadays, CCS discs with 483 and 432 mm diameter (17″ and 19″) are the common types due to their higher loading capacity (Rostami, 2008). On the other hand, the V-shaped discs penetrate the rock with lower normal forces because of their sharp tips but the wear rate of this type is much higher (Balci and Tumaç, 2012). Since the loading capacity of both abrasivity testing devices used in this investigation is limited and also the wear of the scaled down discs must be detectable, the V-shaped discs were selected for the rock cutting tests. Therefore, four scaled down disc cutters using H13 steel were made, including two 54 mm diameter discs (1/8 scale comparing to the 17″ discs) and hardness equal to 54 HRC and the other two 72 mm diameter discs (1/6 scale comparing to the 17″ discs) and hardness equal to 32 HRC. The design, geometry and the mechanical properties of the discs are presented in Fig. 6, Tables 3 and 4, respectively.

2.4. Measurement

The tip width of each 30° on the perimeter of the disc (total 12 points as shown in Fig. 7) is measured both before and after running the cutting tests on the sharp and worn discs, respectively. Accordingly, the average of these 12 measurements are reported as the abrasivity test results. The measurements are done by a binocular using its maximum magnification (32x) as shown in Fig. 8. A digital camera is attached to the binocular to take the pictures of the disc tip. For measuring the tip width, discs are fixed vertically above the lower light source of the binocular set. This method of analyzing the tip width of the disc captures a section of the disc perimeter (Fig. 9) which has a quite similar shape comparing to the worn Cerchar pin when the pin is analyzed using the method proposed by Rostami et al. (2005). A picture of the worn disc tip from the 54 mm disc after performing the tests on Basalt is presented in Fig. 9 c.

2.5. Sample preparation

Three types of rocks are selected including Basalt, Tufa, and Marble. The mechanical properties of the rock samples are listed in Table 3. The range of the UCS for the selected rock types is from 62 MPa for Marble to 123 MPa for Basalt that is a wide enough to cover the rocks with medium to high UCS based on Deere and Miller (1966) strength classification of intact rocks. All of the rock samples are cut and sawn in 10 cm × 10 cm × 15 cm dimensions. Cerchar abrasivity tests were also performed three times on each of the rock samples at normal room temperature of 20 °C (Fig. 10). The average of the three results is presented in Table 5.

Table 3
Geometry of the scaled down discs.

Disc number	d_1 (mm)	d_2 (mm)	d_3 (mm)	W (mm)	t (deg)
1	35	41	54	22	80
2	35	41	54	22	90
3	35	53	72	22	80
4	35	53	72	22	90

Table 4
Mechanical properties of the discs.

Disc number	Density (kg/m^3)	Hardness (HRC)	Young's modulus (GPa)	Yield strength (MPa)	Ultimate strength (MPa)
1	7800	54	215	1000	1200
2	7800	54	215	1000	1200
3	7800	32	170	800	1050
4	7800	32	170	800	1050

3. Results and discussion

3.1. Wear monitoring

Currently, two methods are being used to monitor the wear of the cutting tools in rock abrasivity tests. In the first method, the weight loss of the cutting tool is monitored after performing the test (Farrokh and Kim, 2018; Macias et al., 2016; Sun et al., 2019; Zhang et al., 2018; Dahl et al., 2012). In the second method, which is incorporated in Cerchar abrasivity test, the microscopic change of the cutting tool shape (i.e. tip width of the pin) is recorded and defined as the wear criterion (Alber et al., 2013). Piazzetta et al. (2018) also applied this method to improve abrasivity classification of rocks. In their study, microscopic changes in the surface of the Cerchar pin were investigated using a scanning electron microscope.

In this paper, regarding the second method, the measured tip width of the discs are presented as a function of the accumulated test run for different types of rocks. The main privilege of using this method of monitoring wear is its capability of identifying the wear regime. This feature is applied to distinguish the normal wear of the V-shaped disc tip from the possible deformations. As it will be discussed later when

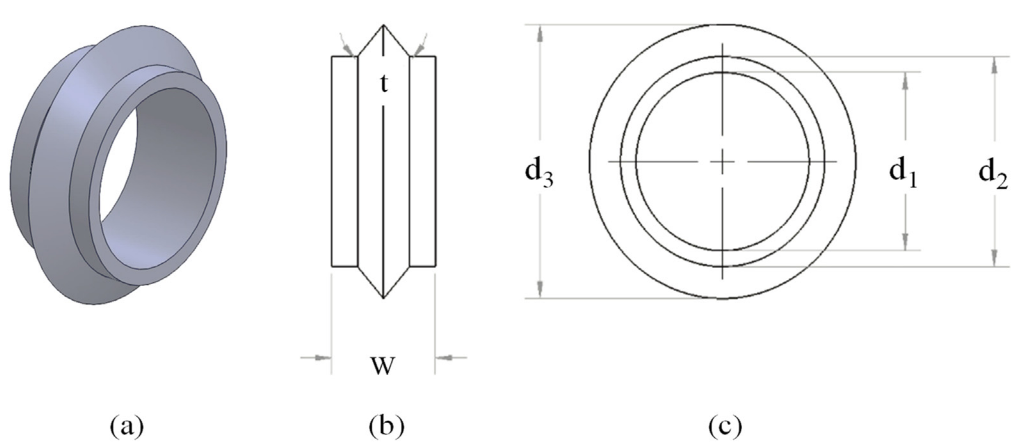

Fig. 6. Schematic views of the disc (a) 3D (b) Side (c) Front.

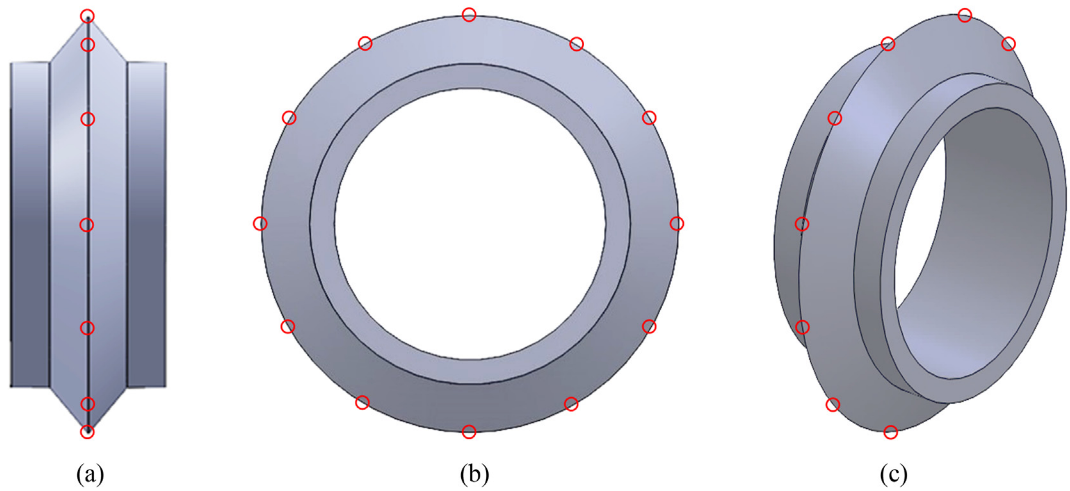

Fig. 7. Selected points on the disc perimeter for tip width measurement (a) Side view (b) Front view (c) 3D view.

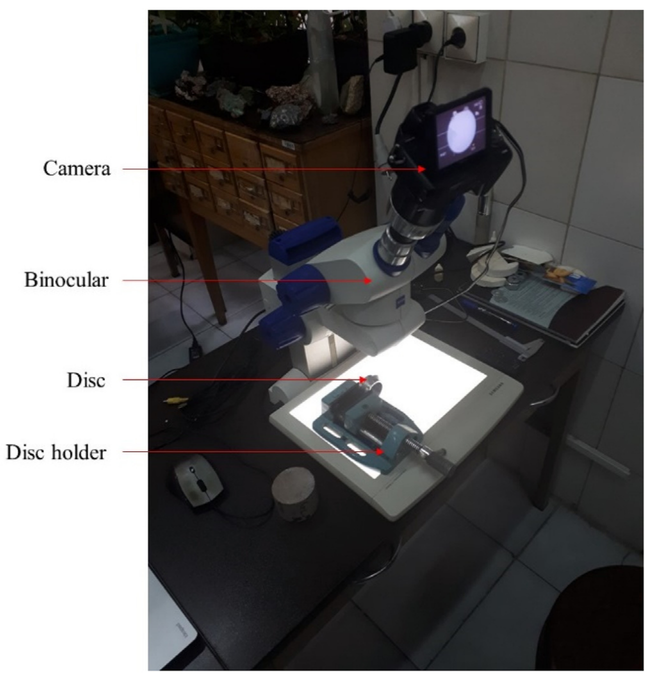

Fig. 8. Binocular and the attached camera for measuring the disc tip width.

presenting the results of the abrasivity tests on the Basalt samples, only the monitoring of the changes in the shape of the disc tip, not the weight loss of the disc, is able to detect the normal wear.

Analysis of the monitored data is performed by introducing new abrasivity indices that is a common approach in rock abrasivity tests. Some of the previously developed abrasivity indices are listed in Tables 1 and 2. As mentioned in Table 1, CAI is defined as the ten times of the tip width (d) of the Cerchar pin where the scratch length is set to 10 mm (Eq. (1)):

$$\mathrm{CAI} = 10\ \mathrm{d} \tag{1}$$

In this study, two abrasivity indices are introduced to classify the results. Since the monitoring approach used in Cerchar abrasivity test is adopted in this study, the definition of the new abrasivity indices follows the same concept. The first index is called the University of Tehran abrasivity Index (UTAI) which is defined as the ten times of the measured tip width (d_f) after performing the first round of the tests (Eq. (2)). Regarding the Cerchar abrasivity index shows the tip width of the Cerchar pin when the sharp pin is worn after scratching the surface of the rock in a pre-determined displacement (Alber et al., 2013), UTAI has a similar concept. According to its definition (Eq. (2)), UTAI represents the tip width of the worn disc when the sharp disc has cut the rock in a cutting length equal to its perimeter, i.e. 170 and 226 mm for the discs with 54 and 72 mm diameter, respectively.

$$\mathrm{UTAI} = 10\ \mathrm{d_f} \tag{2}$$

This cutting length is set for the abrasivity tests to have the sharp disc equally engaged with the rock across its perimeter and therefore, equally worn. The penetration depth of 1 mm is chosen to prevent any damage to the disc tip instead of normal wear. At this penetration depth, every point on the perimeter of the 54 and 72 mm discs has a contact length of 7.3 and 8.4 mm in each rotation of the disc (Fig. 11).

The second index is called the Ultimate Abrasivity Index (UAI) which is defined as the ten times of the measured tip width (d_u) at which the slope of the wear curve, shown in Figs. 13 and 14, has started to be horizontal (Eq. (3)).

$$\mathrm{UAI} = 10\ \mathrm{d_u} \tag{3}$$

The concept of this index displays the effect of the rolling length on the results of the abrasivity tests. According to the findings of Al-Ameen and Waller (1994) and Plinninger et al. (2003) about the influence of the scratching distance on the results of the Cerchar test, 85 percent of the pin wear happens in the first 2 mm of the test (Fig. 12). Then, the wear rate drastically decreases after passing 2 mm that in the next 8 mm of the test run, CAI changes just around 15 percent. Fig. 12 also shows that this drop of the wear rate continuous until 40 mm of the test run, i.e. four times of the standard testing length. In this figure, while the left vertical axis shows the CAI at any testing length, the right vertical axis represents the percentage of the obtained CAI to the CAI at the standard testing length of 10 mm.

A similar trend is observed in the abrasivity tests using scaled down V-shaped discs. According to Figs. 13 and 14, the steepest part of the wear curves for each set of the test belongs to their first round, in which the disc is worn from its sharpest state. As mentioned earlier, UTAI is introduced to represent this part of the wear curves. By continuing the test, a sudden decrease in the wear rate is noticeable until the slope of the wear curves has become horizontal. UAI is defined to categorize the abrasivity of the rocks based on this point where the cutting tool has undergone the majority of its normal wear. From this point forward, continuing the test will mostly cause deformation of the tip of the disc with minor normal wear.

Fig. 13 shows the wear results of the 54 mm disc with 80° tip angle. Due to the high value of the disc hardness (54 HRC) and relatively

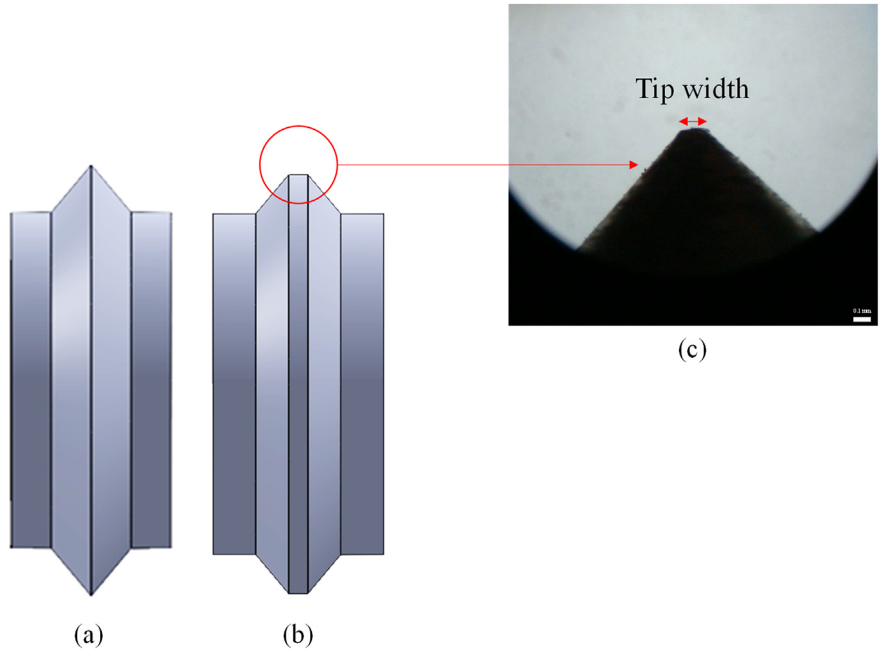

Fig. 9. Tip width measurement (a) Sharp disc (b) Worn disc (c) Magnified worn tip.

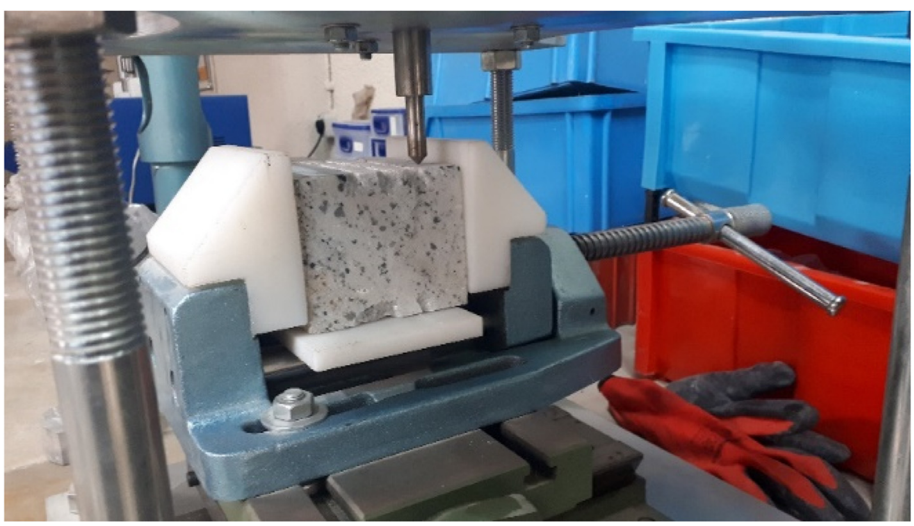

Fig. 10. Cerchar abrasivity test on Marble.

Table 5
Mechanical properties of the three rock samples.

Rock type	UCS (MPa)	Poisson's ratio	Young's modulus (GPa)	φ (deg)	Cohesion (MPa)	CAI
Basalt	123	0.2	65	21	0.8	3.15
Tufa	91	0.24	14	11	4.4	1.63
Marble	62	0.11	63	19	5.1	1.13

medium UCS of Marble (62 MPa), the disc has remained almost unworn. The tip width of the disc has been increased from 0.048 to 0.053 mm which shows only 10 percent change after 5 test run. Abrasivity tests of Tufa show relatively more wear than Marble that is due to the higher UCS of this rock type. The tip width of the disc has been increased 60 percent after the first round and 100 percent after its ultimate abrasivity value.

For Basalt, the wear rate is the highest among all of the first rounds, i.e. 130 percent increase of the tip width by the first run. This extreme wear continuous until the ultimate abrasivity value is reached where the tip width has been increased almost 5.5 times. For the next 510 mm running the test (3 rounds), a negligible wear is measured and the slope of the wear curve is horizontal. Then, the wear starts again after the 1360 mm test run passes with even higher rate comparing to the first rounds. The type of wear is different at this time. In the first rounds, normal wear was observed on the disc tip (Fig. 15 a), while in the last rounds, severe deformation is detectable on the disc tip (Fig. 15 b).

An explanation for this behavior is that until the 850 mm test run, the cutting forces are not adequate to deform the tip. After 1360 mm test run, due to high UCS of Basalt and also bluntness of the disc, the disc has experienced higher cutting forces to preserve the 1 mm penetration depth, as the penetration depth was set to be constant during the rock cutting process. This extreme loading has made some deformations on the disc tip that can be easily seen in Fig. 15 b. The normal wear and the deformation of the disc tip can be determined by drawing the lateral lines

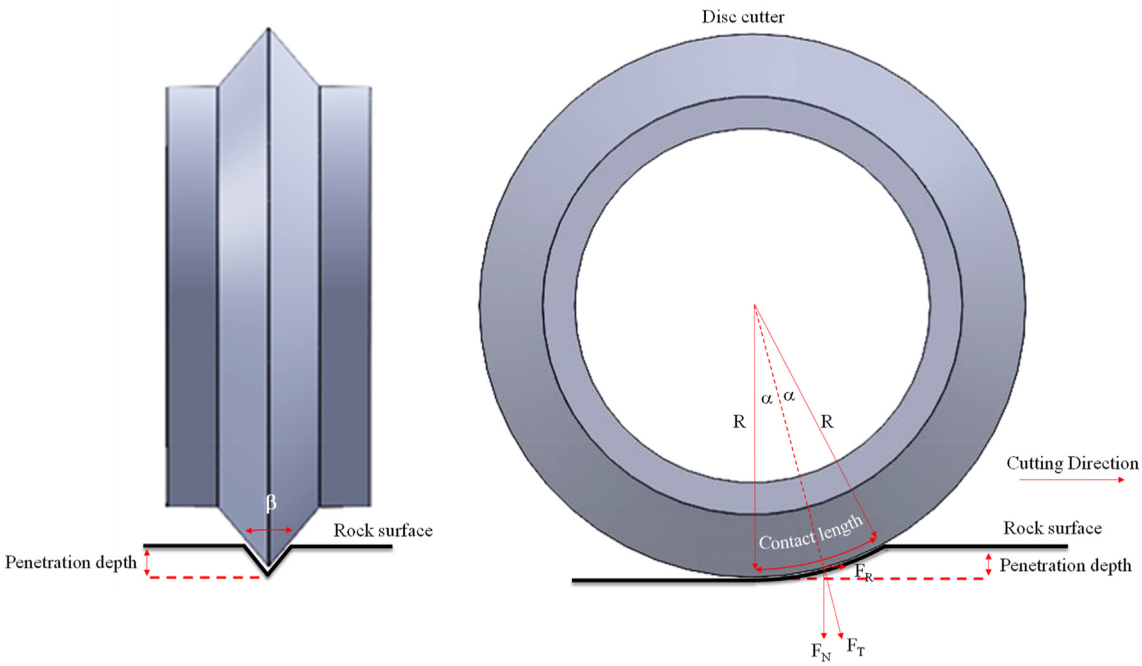

Fig. 11. Geometry of the rock cutting process.

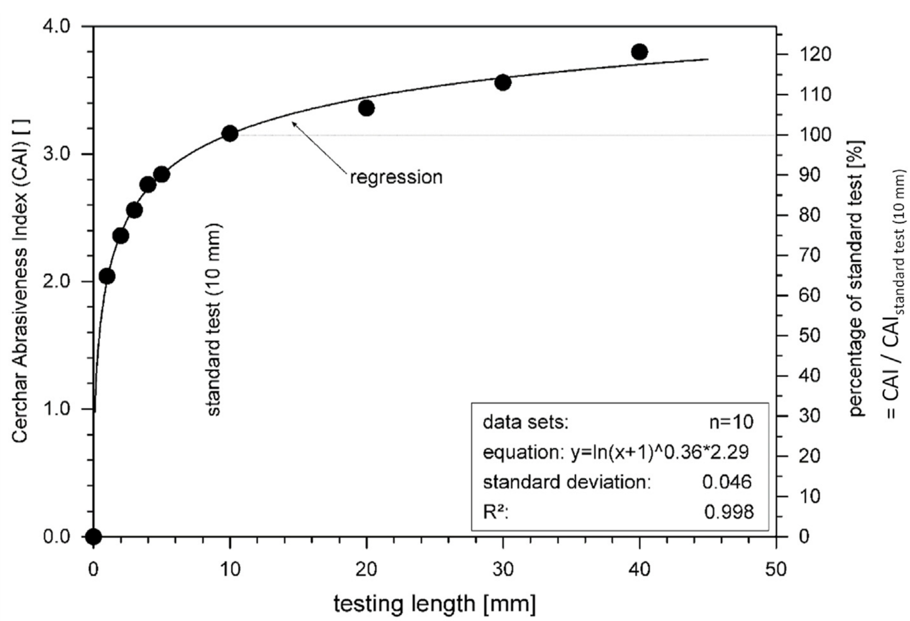

Fig. 12. Plot of CAI versus testing length (Plinninger et al., 2003).

(the red lateral lines) of the disc perimeter. In Fig. 15 b, by drawing the lateral lines, burr is detectable on the outside of the line around the disc tip, while in Fig. 15 a, the triangular section of the disc tip has just been worn without any deformations. Analysis of the tip deformation is beyond the scope of this study.

Fig. 13 also presents the wear results of the 54 mm disc with 90° tip angle. The results of this set of tests show an increase comparing to the 80° tip angle disc. For the Basalt samples, wear rate is the highest of the first rounds. Then, the slope of the wear curve becomes horizontal for almost 510 mm test run (3 rounds) where there is a slight increase of the tip width. It shows that the ultimate abrasivity is reached when the tip width is equal to 0.565 mm that is twice the amount of UAI comparing to the results on the Basalt samples using the 80° tip angle disc. Meanwhile, in the equal test run, i.e. in 850 mm test run, the tip width of the 90° tip angle disc is 0.374 mm which is 30 percent higher than the UAI of the 80° tip angle disc. The change of the tip angle that results in increasing the normal and rolling forces and also modifying the disc shape are some of the reasons for this increase of UAI. Wear alongside with deformation restarts after 2550 mm test run with the lower ratio comparing to the first rounds, similar to the response of the 80° tip angle disc after 1360 mm test run.

For the Tufa samples, there is a slight increase in the wear results comparing to the previous set of the tests but with a similar trend. Since the abrasivity tests on the Marble samples showed almost no wear on the 80° tip angle disc cutter, it was expected that it would show the same behavior on the 90° tip angle disc. Therefore, no tests were performed on

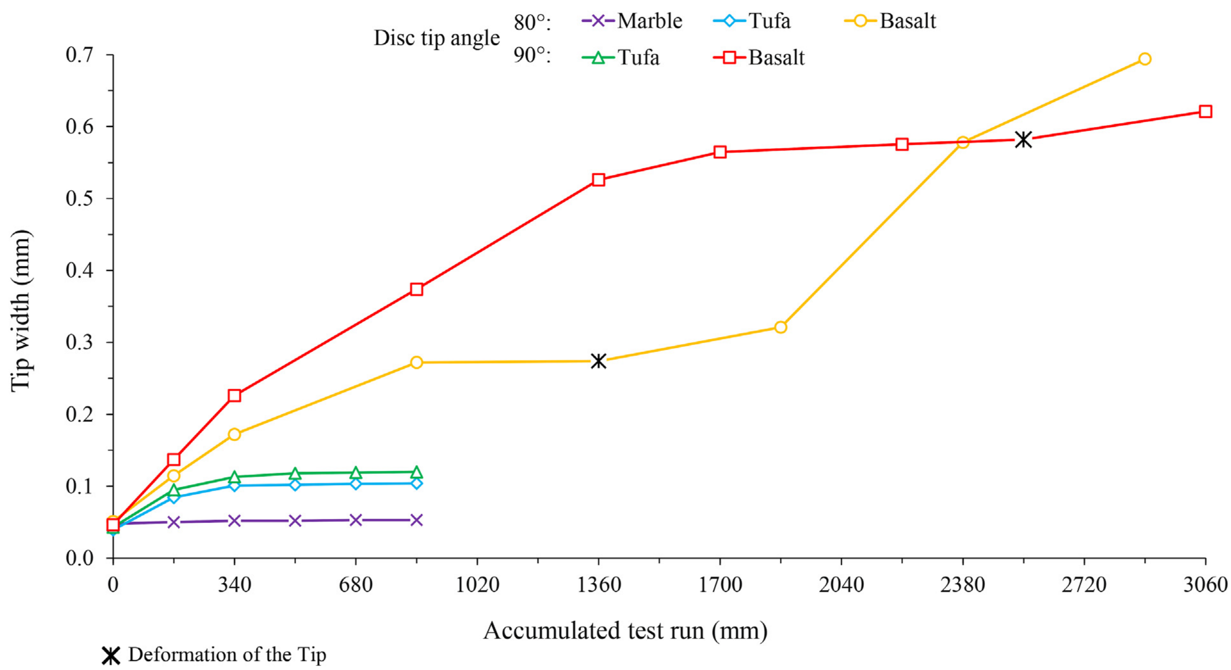

Fig. 13. Wear of the 54 mm discs.

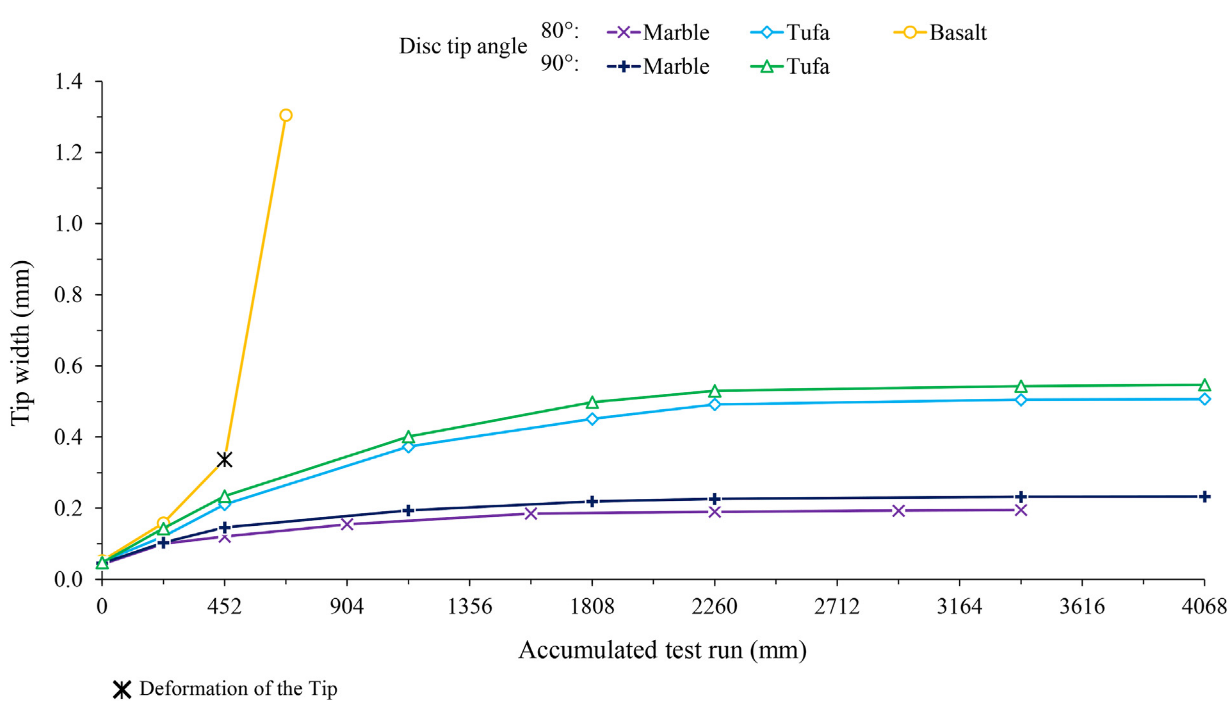

Fig. 14. Wear of the 72 mm discs.

the Marble samples using this disc.

Fig. 14 shows the wear results of the 72 mm discs. Lower hardness of these discs (32 HRC) results in higher wear for the tests on Marble where the tip width has increased 2.7 and 3.8 times until the ultimate abrasivity is reached for the 80° and 90° tip angle discs. The results of the abrasivity tests on Tufa and Basalt show an increase in the amount of UTAI and UAI comparing to the 54 HRC discs. Although the normal wear was observed in the entire tests on the Tufa samples, an extreme deformation happened after the second round on Basalt. The tip width of the disc has been increased 3.7 times between the second and third rounds of the test, equal to 225 mm distance. This extreme deformation is due to the low hardness of the disc and high UCS of the rock. Since studying this extreme deformation was not the subject of this study, no more tests were performed on the Basalt samples using 72 mm discs.

3.2. Cutting forces

The normal and rolling forces acting on the discs are monitored using a dynamometer. Fig. 16 shows an output data of the dynamometer for the 54 mm disc with 80° tip angle.

In this figure, the output forces are presented as the function of the cutting time. In all of the rock cutting tests, the 10 cm cut were performed

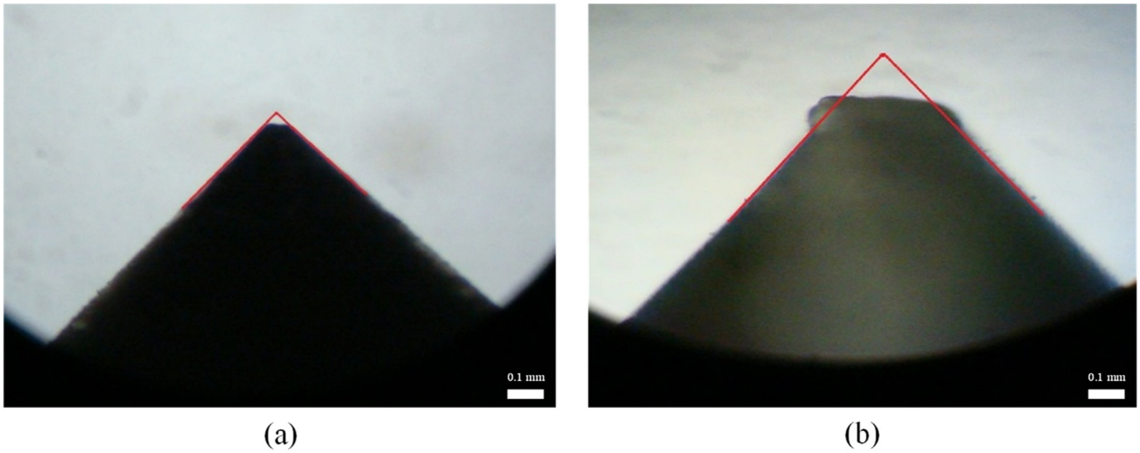

Fig. 15. Types of wear detected on the disc tip (a) Normal wear (b) Deformation.

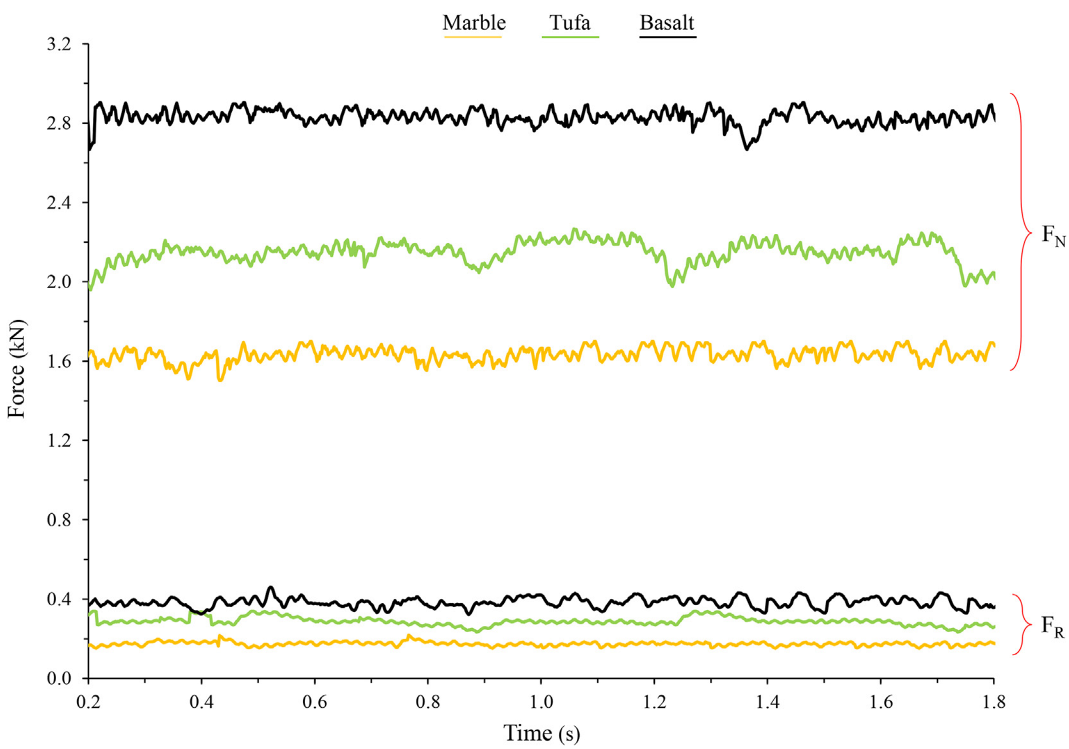

Fig. 16. Normal and rolling forces on the 54 mm disc with 80° tip angle.

in 2 s and the average of the output forces between t = 0.2 s and t = 0.8 s were considered as the resulting normal and rolling forces of that specific test. The normal and rolling forces graphs of the other discs are almost the same as Fig. 16, meanwhile in those, the recorded normal and rolling forces oscillate around different levels of forces. For example, in Fig. 16, the average normal force acting on the disc 1 for the test on the Basalt samples is 2.75 kN, while in the graph for the disc 2, this average value is 3.36 kN.

The fluctuation of the forces around an average value is due to the rock cutting process that consist of 4 steps (Henneke and Kubler, 1981). At first, the disc touches the surface of the rock and slightly penetrates, causing local damage to the rock. At the next step, the disc continues penetrating the rock until it reaches the predetermined penetration depth. Then, the normal and rolling forces increase until they overcome the UCS of the rock in front of the disc. At the exact moment of the rock fragmentation and chipping, those forces reach their highest value and cracks are developed to the surface of the rock. At last, the disc rolls forward which results in the drop in the forces. By making contact between the rock and the disc again, the aforementioned process repeats. Regarding Fig. 16, this process is so quick and the duration between the two peaks is less than 20 ms.

3.3. Abrasivity indices, UCS, and cutting forces

Table 6, presents the abrasivity indices, CAI, and the monitored average cutting forces against the specifications of the related tests. The plots of the obtained abrasivity indices against the UCS and CAI are shown in Fig. 17 a–d. As shown in Eqs. (4) and (5), the following correlations exist between UTAI, UAI and UCS for the 54 HRC discs with R^2 of 0.93 and 0.90, respectively:

$$UTAI_{54\ HRC} = 0.01UCS - 0.24 \tag{4}$$

Table 6
Abrasivity tests results.

	D (mm)	H[a] (HRC)	P[b] (mm)	Tip angle (deg)	UCS (MPa)	CAI ()	UTAI ()	UAI ()	UTAT (kN)		R–P Model (kN)		Relative error (%)	
									F_N	F_R	F_N	F_R	F_N	F_R
Disc 1	54	54	1	80	123	3.15	1.15	2.72	2.75	0.37	2.93	0.4	6.14	7.50
Disc 1	54	54	1	80	91	1.63	0.84	1.01	2.14	0.29	2.20	0.3	2.73	3.33
Disc 1	54	54	1	80	62	1.13	0.5	0.52	1.55	0.19	1.47	0.2	5.44	5.00
Disc 2	54	54	1	90	123	3.15	1.37	5.65	3.36	0.46	3.49	0.48	3.72	4.17
Disc 2	54	54	1	90	91	1.63	0.95	1.18	2.57	0.35	2.62	0.36	1.91	2.78
Disc 2	54	54	1	90	62	1.13	–	–	–	–	1.75	0.24	–	–
Disc 3	72	32	1	80	123	3.15	1.58	–	3.28	0.38	3.39	0.4	3.24	5.00
Disc 3	72	32	1	80	91	1.63	1.2	1.20	2.48	0.31	2.55	0.3	2.75	3.33
Disc 3	72	32	1	80	62	1.13	1.01	1.00	1.61	0.18	1.70	0.2	5.29	10.00
Disc 4	72	32	1	90	123	3.15	–	–	–	–	4.04	0.48	–	–
Disc 4	72	32	1	90	91	1.63	1.43	5.30	3.05	0.32	3.07	0.36	0.65	11.11
Disc 4	72	32	1	90	62	1.13	1.03	2.26	1.96	0.22	2.02	0.24	2.97	8.33

[a] Hardness.
[b] Penetration.

$$UAI_{54\ HRC} = 0.05\exp\ (0.03UCS) \tag{5}$$

These strong correlations between the abrasivity indices and UCS are observed in the previous investigations as well. As mentioned earlier in Table 2, Farrokh and Kim (2018) studied the wear of the scaled-down CCS discs. They introduced an abrasivity index called DWI, which represents the weight loss of the disc after 7.5 m of performing the rock abrasivity test, and showed that a linear correlation with R^2 of 0.74 exists between DWI and UCS, as presented in Eq. (6):

$$DWI = 1.61UCS + 100.02 \tag{6}$$

By comparing Eq. (4) with Eq. (6), it is obvious that a similar trend exist between UTAI, DWI, and UCS, which demonstrates the sensitivity of the tests using disc cutters to the strength properties of the rocks and the repeatability of the values obtained as their indices. Eqs. (7) and (8) show the correlations between UTAI, UAI, and CAI for the 54 HRC discs with R^2 equal to 0.84 and 0.92, respectively:

$$UTAI_{54\ HRC} = 0.32CAI + 0.28 \tag{7}$$

$$UAI_{54\ HRC} = 0.41CAI^{1.96} \tag{8}$$

Researchers has studied the wear of the disc cutters and established the relationship between their results and other widely used abrassivity indices such as CAI. Sun et al. (2019) studied the wear of CCS discs and proposed a correlation between the wear weight of the disc (W) after 100 m of rock cutting test and CAI (Eq. (9)):

$$W = 0.78CAI^2 \tag{9}$$

Comparison of Eq. (8) with Eq. (9) shows a notable similarity of the relationships between UAI, W, and CAI, which verifies the repeatability of the abrasivity tests using disc cutters and the applicability of the introduced abrasivity indices. A reason for the similarity of Eqs. (4) and (6) between the linear relationships of UTAI, DWI and UCS is that both UTAI and DWI are obtained after shorter rock cutting length, i.e. UTAI after one round and DWI after 7.5 m of rock cutting tests. With the same reasoning, the similarity between the power function of the correlations between UAI, W, and CAI in Eqs. (8) and (9) is justifiable because UAI and W are defined to represent the wear for a longer rock cutting length, i.e. UAI after several rounds and W after 100 m.

The average value of the output forces (section 3.2) are also in good agreement with previous studies as well. Table 6 presents the average of the cutting forces in this study and estimated values from the theoretical Roxborough and Phillips (R–P) model (1975). According to this model, cutting forces acting on the V-shaped disc during the rock cutting process is estimated by Eq. 12 and 13:

$$F_N = 4\sigma\ (Dp^3 - p^4)^{1/2}\ \tan\ (\beta/2) \tag{10}$$

$$F_R = 4\sigma\ p^2\ \tan\ (\beta/2) \tag{11}$$

where D is the disc diameter, p is the penetration depth, and σ is the UCS of the rock sample. The geometry of the rock cutting process is shown in Fig. 11. In this study, since the penetration depth is constant in all abrasivity tests, i.e., 1 mm, cutting forces on each disc have linear relationship with UCS. As presented in Table 6, comparison of the monitored cutting forces with the R–P model shows that the relative error is so small for each set of the rock cutting tests, which verifies the abrasivity testing process and the monitored forces.

Fig. 17e and f show the abrasivity indices against the monitored normal forces. Since from the theoretical R–P model (Eqs. (10) and (11)), cutting forces are the functions of UCS and a linear correlation is obtained between UTAI and UCS (Eq. (4)), a strong relationship is expected between the abrasivity indices and cutting forces. However, as the cutting forces depend on the UCS of the rocks, the relationships between the abrasivity indices and cutting force are not established in this study to avoiding any misleading of presenting the cutting forces as separate variables.

4. Conclusion

Estimating the wear of a cutting tool is a great challenge since the performance of the mechanized tunneling machines directly affects the duration and costs of the projects. University of Tehran abrasivity test is introduced to estimate the wear of the disc cutters by performing laboratory rock cutting tests using scaled down discs. In this test, comparing to the Cerchar pin, there is more similarity between the shape of the cutting tool and real-scale disc cutters and besides, this tool penetrates the rock while having its free rolling motion. Therefore, the test closely resembles the rock cutting process and consequently, those parameters that affect the disc wear. The method of measuring the tip width of the cutting tool, instead of its weight, is utilized in this study that makes it possible to distinguish the normal wear from the deformations, as it is necessary to differentiate these types of wear to optimize the performance of the disc cutters before they undergone excessive deformations. Two abrasivity indices are defined, namely UTAI and UAI, to easily interpret the relationships between the mechanical properties of the rocks and the abrasivity test results. Each of these indices has a similar concept comparing to the Cerchar abrasivity index, as UTAI represents the wear of the sharp cutting tool and UAI displays the effect of the testing length. The correlations between the abrasivity indices, UCS and CAI are established, which shows strong relationships between them. This means that the introduces abrasivity test is capable enough to cover all aspects of the tribology system of a rock cutting procedure using disc cutters. Moreover, UTAI and UAI are highly sensitive to the mechanical properties of the discs and rock samples, which makes them good representatives of the disc wear. Comparison of these equations and those of the previous studies also shows the similarity between them that

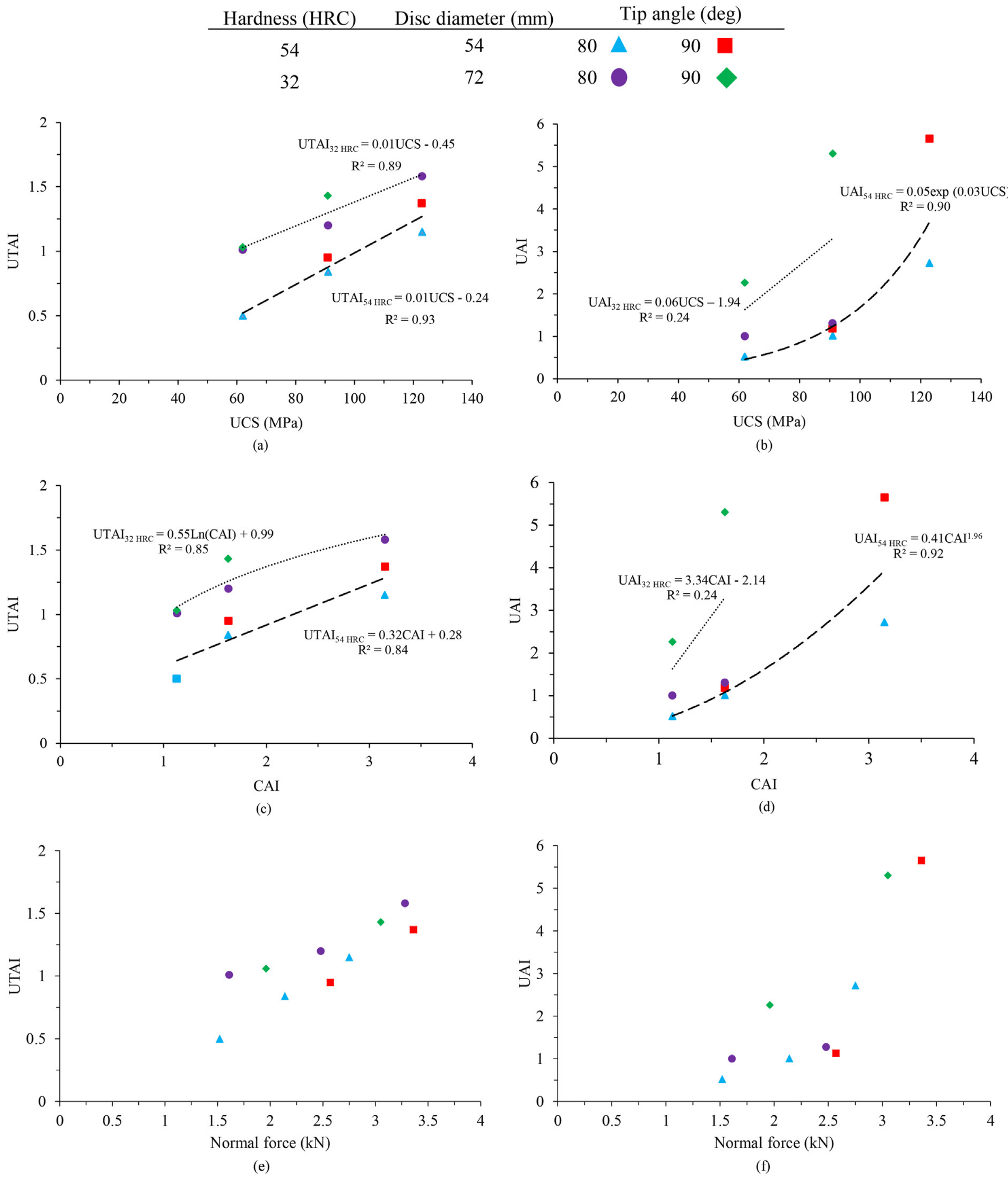

Fig. 17. Correlation between the abrasivity tests results (a) UTAI – UCS (b) UAI – UCS (c) UTAI – CAI (d) UAI – CAI (e) UTAI – Normal force (f) UAI – Normal force.

perfectly demonstrates the repeatability of the output data of the recently designed abrasivity tests using scaled down disc cutters. Moreover, the testing process is verified by comparing the monitoring cutting forces with theoretical model in the previous studies. Since the University of Tehran abrasivity test closely resembles the rock cutting process using disc cutters, it is able to distinguish between the normal wear and deformation, and its results are in good agreement with the mechanical properties of rocks, using this method can enhance the accuracy of the rock abrasivity classifications. Moreover, some features of this method increase the feasibility of worldwide utilization of this test including the small sample preparation, fast testing procedure, and simple testing apparatus with low capacity that is widely accessible.

CRediT authorship contribution statement

Maziar Moradi: Writing – original draft, Methodology, Data curation, Conceptualization. **Mohammad Hossein Khosravi:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Jafar Khademi Hamidi:** Writing – review & editing, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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