



Use of rock microscale properties for introducing a cuttability index in rock cutting with a chisel pick

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Abstract

Accurate estimation of rock cuttability is crucial for selecting and design of mechanical excavators in mining and civil engineering practices. This study is to introduce the intact rock cuttability index (IRCI) using three simple and easily accessed intact rock microscale parameters. Assuming that an intact rock consists of mineral grains (materials), cement or matrix and pores, three parameters of rock texture coefficient (TC), Cerchar abrasivity index (CAI), and porosity were selected to be included in IRCI equation. Small-scale rock cutting tests with a simple chisel pick were conducted on very low to medium strength rock specimens to calculate the specific energy (SE) as an indicator of rock cuttability. Accordingly, the correlations between rock physical and mechanical properties, IRCI, and SE were investigated. The analysis results showed that the rock strength parameters (i.e., UCS and BTS) are not well described by texture coefficient, while they were well correlated with the cuttability index developed based on rock microscale properties. The results also showed that there is a strong correlation between the intact rock cuttability index and specific energy. These findings, although promising, are preliminary. Hence, further studies are underway with additional data sets to examine the validity and extend the model to actual size cutting tools.

Keywords Mechanical excavation · Rock cutting test · Specific energy · Texture coefficient

Introduction

In mining and civil engineering practices, mechanical miners and excavators such as roadheaders, surface miners, continuous miners, and shearer loaders are widely employed for rock excavation and coal mining purposes. In mechanical excavation, having prior knowledge of the cuttability of rock is crucial for selecting and designing the machine and predicting its

performance. Rock cuttability is defined as the ease or difficulty of rock breakage by mechanical tools and usually expressed by specific energy (SE) as well as cutting forces. SE defined as the energy/work required to excavate a unit volume/weight of rock, has been generally used for analyzing the efficiency of rock-working process (i.e., rock penetration and fragmentation) in different scales, for example, in order to represent the concept of machinability, drillability, and cuttability (e.g., by Barker 1964; Teale 1965; Evans and Pomeroy 1966; Roxborough and Rispin 1973; Suwannapinij 1975; Bilgin 1977; Fowell and Pycroft 1980).

Rock cuttability and specific energy can be determined directly from cutting trials in the laboratory. However, the laboratory measurement of SE requires the use of small- or full-scale testing facilities which are more widespread nowadays.

The chisel picks are usually the main cutting tools in small-scale testing facilities, but they are not commonly used in mechanical excavators. Use of such small-scale tool makes it easier and more convenient to carry out basic study on cutting mechanism and correlating the cuttability with rock properties because of their geometrical simplicity. As noted by Bilgin et al. (2014), the findings from these studies can be

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used to modify and extend their application into complex-shaped and full-scale cutting tools.

Rock cutting experiments are time consuming and expensive and require collecting and preparing representative specimens. Hence, the estimation of rock cuttability and specific energy from easily measured rock physical and mechanical properties has been suggested as an alternative approach by several researchers (e.g., Fowell and Pycroft 1980; Cheraghi Seifabad 1992; Balci et al. 2004; Goktan and Gunes 2005; Tiryaki and Dikmen 2006; Bilgin et al. 2006; Comakli et al. 2016; Yasar et al. 2015).

A comprehensive review of the published literature given in next section indicates that the rock cuttability has been an important concept in mechanical excavation studies, and as such has been the subject of many investigations. However, even with laboratory-scale studies, cutting tool–rock interaction is a complex research area that still needs to be explored further. Furthermore, there are only few studies that investigated into drag pick cutting performance and SE focusing on microscale petrographic properties and most studies rely on block or core specimen–based experiments such as uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) as input parameters. Moreover, a limited number of these studies have put together simultaneously more than one single parameter into rock cuttability analysis and estimation of SE.

The main purpose of the present study is to suggest a cuttability index for predicting SE obtained from a small-scale linear cutting test. Since grains (materials), cement or matrix, and pores are three components of rock material, three representative testing methods are taken into consideration in order to obtain the three input parameters. Accordingly, Cerchar abrasivity index (CAI), texture coefficient (TC), and porosity are selected for expressing grains hardness, matrix structure, and pore volume, respectively, in suggested intact rock cuttability index (IRCI). Eleven rock and rock-like concrete specimens are selected for mechanical tests and textural characteristics. Rock cutting tests are conducted on core samples of very low to moderate compressive strength using a simple flat chisel pick. The correlation of rock mechanical parameters with its textural properties is investigated. Also, the relationship of SE obtained from linear cutting test is examined as a function of three intact rock microscale parameters and suggested rock cuttability index.

Background

Many studies have examined the relationship between rock physio-mechanical properties and its cuttability (e.g., McFeat-Smith and Fowell 1977; Fowell and Pycroft 1980; Howarth and Rowlands 1987; Ersoy and Waller 1995; Azzoni et al. 1996; Tuğrul and Zarif 1999; Burgi et al. 2001;

Balci et al. 2004; Tiryaki and Dikmen 2006; Alber and Kahraman 2009; Gupta and Sharma 2012; Yasar et al. 2015). A comprehensive literature review on rock cuttability and its relationship with rock physical/mechanical parameters for various cutting tools may be found in recent studies carried out by Yasar and Yilmaz (2017) and Tumac et al. (2018).

In brief, two research streams related to rock/coal cuttability when using drag bits can be distinguished: theoretical and empirical models. A look into the literature reveals that there exist some different theories and models focusing on the rock/coal cutting mechanism or failure mode in order to determine the cutting forces acting on a drag bit. Among them, the models developed by Evans (1962) for pointed and chisel picks and Nishimatsu (1972) for the chisel pick are the most recognized ones which have been widely used in mining and civil engineering practices. Roxborough and Liu (1995) proposed changes to the Evans' cutting theory for pointed picks. The developed model considers the effect of friction and radius of the hole for pointed picks. Goktan (1997) also modified Evans' theory for pointed pick. The model was then modified to a semi-empirical model by Goktan and Gunes (2005). Based on edge chipping experiments conducted on four different sandstones, Bao et al. (2011) developed a model to estimate the peak indentation force of pointed picks.

Theoretical models, although led to a better understanding of rock/coal cutting process, as noted by Bilgin (1977), the cutting force estimated from these models remains different in some cases from that of measured force in the practice, mainly due to the major simplifications considered in the model and the complex nature of rock formations.

In recent years, there has been an increasing amount of literature focusing on semi-empirical and empirical models for prediction of rock cutting force. For example, based on the experimental data of previous researchers, Goktan (1995) developed a semi-empirical model for estimating the cutting forces of chisel picks. In empirical models developed for rock cuttability assessment for drag bits, different rock physical/mechanical parameters were utilized. For instance, researches carried out by McFeat-Smith and Fowell (1977), Fowell and Pycroft (1980), Goktan (1995), Altindag (2003), Balci and Bilgin (2007), and Tiryaki et al. (2010) for correlating rock physical and mechanical parameters with rock cuttability (cutting/normal forces and SE) obtained from small-scale cutting tests could be noted.

In the field-scale studies, as noted by Fowell and Pycroft (1980), for years, the UCS of intact rock was used to assess the performance of boom-type excavators. They also noted that in many cases it has been observed that the compressive strength alone is not a good indicator of rock machinability. Meanwhile, the rock strength parameters have been widely used for developing cuttability assessment empirical models in laboratory-scale studies. For instance, Copur et al. (2001)

investigated the relationship of optimum SE obtained from full-scale tests with compressive, and tensile strength of rock material. It was reported that the optimum SE can be predicted based on a correlation with UCS and BTS values. By running full-scale linear cutting tests in the laboratory, Balci et al. (2004) proposed statistical equations for estimation of optimum SE based on mechanical rock properties including UCS, BTS, dynamic and static elasticity moduli, and Schmidt hammer rebound values in order to assess the performance of roadheader. The results of their study show that the strongest relationships are found by using UCS and BTS. Also, having conducted a wide range of full-scale conical pick cutting tests, Bilgin et al. (2006) found that the measured cutting forces were best correlated with UCS and BTS. Using the full-scale rock cutting data set from Balci and Bilgin (2007), Tiryaki et al. (2010) developed six different empirical equations for predicting the mean cutting force of pointed picks. Rock properties and cutting geometry parameters such as spacing and depth of cut were incorporated in this study. Also, Tiryaki and Dikmen (2006) noted that UCS may be a reliable predictor parameter of the rock cuttability for a particular rock type, since reasonable correlations have not been reported between the UCS and rock cuttability for evaporates such as gypsum and anhydrite. Part of the reason for this is perhaps the UCS does not seem to be a representative property for cuttability in rock cutting employing drag tools with scratching effect on the rock surface and limited cutting depth, although it may be a good rock resistance index for the use of indenter (roller) tools.

It seems obvious that rock physical/mechanical properties are influenced by its mineralogical and textural properties. Meanwhile, the meaningful relationship between these two rock micro- and macro-scale parameters has been found in several studies (e.g., Merriam et al. 1970; Irfan and Dearman 1978; Baynes and Dearman 1978; Onoreda and Asoka 1980; Tugrul and Zarif 1999; Yusof and Zabidi 2016; Sun et al. 2017). Hence, in another group of empirical rock cuttability studies, attempts have been made to correlate the cuttability with rock microscopic parameters and textural characteristics including mineral composition, morphology, and spatial distribution of mineral grains, porosity, and micro-cracks. For example, the relationship between rock texture and specific energy in addition to the mechanical parameters was investigated by Tiryaki and Dikmen (2006).

In present study, the intact rock cuttability index (IRCI) is introduced, utilizing the rock texture coefficient (TC) for rock cuttability assessment. TC as a dimensionless quantitative measure of rock texture was developed by Howard and Rowlands (1987) to predict the drillability and rock strength properties.

Since its conception, TC has been used in several researches for different purposes. Ersoy and Waller (1995)

reported that the TC for crystalline rocks is relatively high, while the TC for sedimentary rocks is medium or low. They also observed a correlation between strength property and TC. However, they noted that TC is not sufficient alone to assess all rock properties, because many rock mechanical properties such as hardness and abrasiveness of rock constituents, bonding structure, and type and degree of cementation are not quantitatively included. Also, Azzoni et al. (1996) examined the relation between TC and rock mechanical and physical properties and concluded that TC provides possibly a general guideline for description and classification of rocks, but not for accurate prediction of their mechanical properties. As an efficient indicator of rock mechanical strength, it requires to be integrated with other important petrographical elements, such as porosity and mineralogical composition. Ozturk et al. (2004) used the cutting test results from a research project carried out by Bilgin and Shahriar (1987) to correlate the mechanical properties and cuttability of rocks with textural properties. They also found a good correlation between rock cuttability and TC. Gupta and Sharma (2012) researched relationship between textural, petrophysical, and mechanical properties of quartzite. In their study, the texture coefficient shows an inverse relationship with the seismic wave velocity and there is a strong direct relationship between TC and UCS. More recently, Tumac et al. (2018) investigated the effect of textural properties of natural stones such as texture coefficient, packing weighting, and grain size on the cutting performance of a standard chisel tool. The results obtained from their experiments revealed that the chisel cutting performance can be predicted based on TC especially with higher reliability at lower depths of cut.

Experimental studies

Rock samples

Nine rock and two cement-based concrete specimens, ranging from very low to high strength according to Bieniawski (1989)-suggested classification for intact rock UCS, were collected and examined in this study. Specimens include sand quartzite (SQJ), two sandstones from Shemshak formation (SA₁ and SA₂), two sandstones from Upper Red Qom formation (SR₁ and SR₂), marl (MK), Andesite (AK), Syenite (SK), Andesite trachyte (AT), and two rock-like cement-based concretes (CM₁ and CM₂). Block rock specimens were collected from nearby construction projects, transported to the laboratory, and then prepared for extracting required samples. The cutting tests were performed on very low to medium strength

rock core samples due to the limitations stemming from the capacity of the cutting machine.

Mechanical and physical tests

The rock mechanical and physical tests were performed according to suggested methods by International Society for Rock Mechanics (ISRM 2007). Also, porosity and dry density were calculated as physical properties of rock specimens.

Cerchar abrasivity index

Since its introduction, the Cerchar test has been accepted by the researchers, consultants, and contractors to determine the rock abrasivity. The Cerchar abrasion test is a convenient and commonly used method to assess the abrasiveness of rock (Ersoy and Waller 1995). In the literature, different arguments are available regarding the test. West (1989) noted that the Cerchar abrasivity index (CAI) is mainly determined by the mineralogical composition of the rock, but later the study of Al-Ameen and Waller (1994) has confirmed the importance of the combined influence of both cementing materials (rock strength) and the total abrasive mineral content. They reported that, for example, a high strength ironstone with the UCS of 140 MPa consisting predominantly of siderite had a high CAI of 1.33 and a low strength (20 MPa) sandstone containing highly abrasive minerals had a CAI of only 0.39.

The idea of using CAI in the present study comes from the similar mechanism in Cerchar test and rock cutting with drag tools. In both cases, the rock surface is scratched by a steel tool of known hardness. Moreover, the CAI can represent both mineral content hardness and cementation of the intact rock.

In this study, the West design of Cerchar test apparatus has been used. The test was carried out on the eleven rock and rock-like samples according to the recommendations of Alber et al. (2014). The procedure is repeated a minimum of five times in two scratching directions (perpendicular to each

other) on the rock surface, always using a new or resharpened steel pin.

The CAI results for eleven rock samples along with abrasiveness classification are summarized in Table 1. From the CAI data given in the table, it can be followed that the specimens tested in this study are described as extremely low to high abrasive rock in accordance with the classification of CAI suggested by Alber et al. (2014).

Textural coefficient

The rock texture can be used as an input for predicting the rock drillability and cuttability, and its mechanical and wear performance (Ersoy and Waller 1995). Up to 1987, the texture of the rocks was expressed qualitatively and since then the texture coefficient presented by Howarth and Rowlands (1987) considered the geometric properties of the grains in the rock quantitatively. A number of researchers have demonstrated that there is a good relationship between TC and rock mechanical properties such as cuttability and drillability (Howarth and Rowlands 1987; Ersoy and Waller 1995; Azzoni et al. 1996; Tuğrul and Zarif 1999; Tiryaki and Dikmen 2006; Alber and Kahraman 2009; Gupta and Sharma 2012; Ozturk and Nasuf 2013; Tumac et al. 2018).

The textural coefficient is calculated through Eq. (1):

$$TC = AW \left[\left(\frac{N_0}{N_0 + N_1} \times \frac{1}{FF_0} \right) + \left(\frac{N_1}{N_0 + N_1} \times AR_1 \times AF_1 \right) \right] \quad (1)$$

where TC is textural coefficient, AW is grain packing weighting, N_0 is number of grains whose aspect ratio is below a pre-set discrimination level, N_1 is number of grains whose aspect ratio is above a pre-set discrimination level, FF_0 is arithmetic mean of discriminated form-factors, AR_1 is arithmetic mean of discriminated aspect ratios, and AF_1 is angle factor, quantifying grain orientation.

Details of the method for obtaining the parameters of the equation are available in Howarth and Rowlands (1987). As followed from Eq. (1), the texture coefficient only takes into account the geometric arrangement of the grains and does not consider their hardness and quality of the cement or matrix. Therefore, in the present study, TC is used along with two additional rock parameters for estimating rock cuttability.

Three petrographic thin sections were taken into consideration for each rock sample in directions of parallel, normal, and random (oriented 45° from the surface) to rock core surface, as shown in Fig. 1.

Under a petrographic microscope, thin sections were inspected and the relevant photos were taken with a digital camera. Accordingly, the photos were imported into an image processing software. Prior to analyzing images, the software

Table 1 CAI measurement results for eleven specimens and the abrasiveness classification

Sample	CAI	Classification
SQJ	3.145	High
SR1	0.727	Very low
SR2	0.250	Extremely low
SA1	3.055	High
SA2	1.667	Low
M.K	0.226	Extremely low
CM1	1.338	Low
CM2	2.754	Medium
S.K	1.916	Low
AT	1.451	Low
AK	1.658	Low



Fig. 1 Preparation of thin sections from core sample in three directions

was calibrated using a reference area enclosing four shapes of specific geometry. In Table 2, the geometric dimensions calculated by the software (M') are compared with the predetermined dimensions (M). It can be followed from the table that there is a good agreement between the real values and those calculated by the software.

After software calibration, thin sections were analyzed in order to calculate the geometric parameters and the texture coefficient, as seen in Fig. 2. TC relevant parameters including grains max ferret's diameter, min ferret's diameter, perimeter, and area were calculated. For each thin section, minimum 300 grains were considered.

Table 3 presents different parameters of textural coefficient. TC1 is textural coefficient when AW (packing density) is ignored. As seen, SQJ as a volcanic rock specimen without cementation has an AW value of 1 and the maximum TC compared with all other specimens.

Small-scale linear cutting test

In this study, a small-scale linear cutting machine (SSLCM), developed at Tarbiat Modares University, was used to evaluate the cuttability of rock samples. The SSLCM setup consists of a modified hydraulic shaping machine, a customized dynamometer, and a data acquisition system. The rig has a power of 5.9 kW and a maximum stroke of 900 mm (Mohammadi et al. 2020).

Seven very low to medium strength rock samples namely SR1, SR2, MK, CM1, CM2, SK, and AT (i.e., sedimentary rock and hand-made rock like samples) were selected for rock cutting tests. The remaining four samples were not tested due limitations mainly related to power of the cutting machine and

configuration of the current dynamometer for cutting high strength rocks.

A chisel tool having tip width (W) of 12 mm, rake angle (α) of 0° , and clearance angle (β) of 12° was used for cutting tests in this study. The selected flat chisel tool is consistent with similar studies in the literature. Roxborough (1973) and Mc Feat-Smith (1975) suggested to use a chisel tool having a rake angle of -5° and clearance angle of 5° in linear rock cutting test; however, numerous studies in the literature have used positive, zero, and negative rake angles and clearance angle between 0 and around 12 degrees (e.g., Bilgin 1977; Goktan 1990; Balci and Bilgin 2007; Yasar and Yilmaz 2017; Mohammadi et al. 2020).

All cutting tests were conducted at 2-mm depth of cut (d) in unrelieved cutting mode. The depth of cut has been fixed after performing a series of cutting trials at deeper depths of cut up to 4 mm on rock specimens including SR1 and MK and realizing the direct linear relationship between depth of cut and cutting force. Since the forces exerted on the currently used dynamometer have a limiting role, the d was kept constant in this study in order to prevent excluding more rock specimens from data sets and further analysis. Furthermore, the findings reported by Tumac et al. (2018) revealed that TC values generally show stronger correlation with rock cuttability at the lower depth of cut values (1.5–2.5 mm).

The tests were repeated four times for each rock specimen and the results were averaged. All tests were conducted at cutting velocity of 12 cm/s, at normal room temperature and humidity. A sketch of the chisel tool and the core cutting test are shown in Fig. 3.

Table 2 Comparison of real (M) and software (M') calculated TC parameters

	AW	$\frac{N_0}{N_0+N_1}$	$\frac{1}{PF_0}$	$\frac{N_1}{N_0+N_1}$	AR ₁	AF ₁	TC ₁	TC
M	0.25	0.5	1.15	0.5	3.03	1	1.97	0.49
M'	0.24	0.5	1.18	0.5	3.01	1	2.09	0.50

Fig. 2 Reference area and boundary of grains

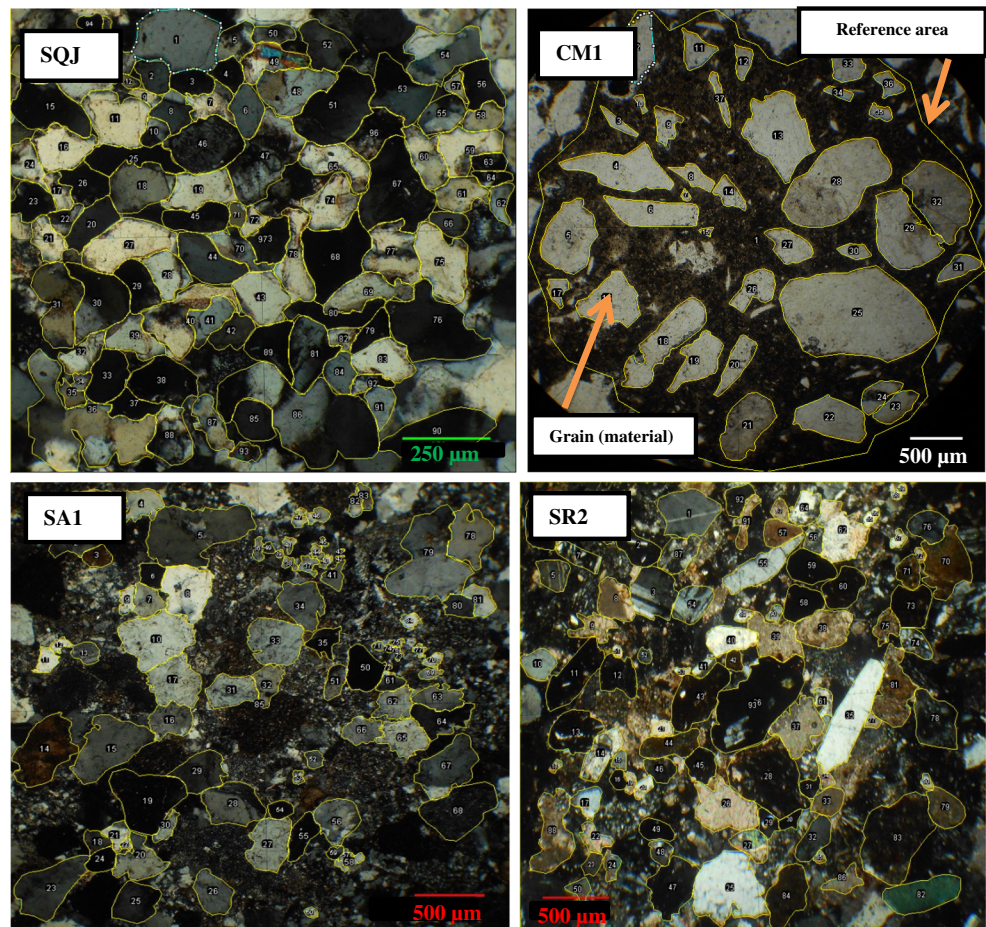


Figure 4 shows SR2 core samples of 76 mm in diameter were firmly clamped in the vise and cut in 2 mm cutting depth. The length of cut is measured after each test, and the debris produced by the cut is collected and weighed for determination of SE. SE is calculated by using Eq. 2.

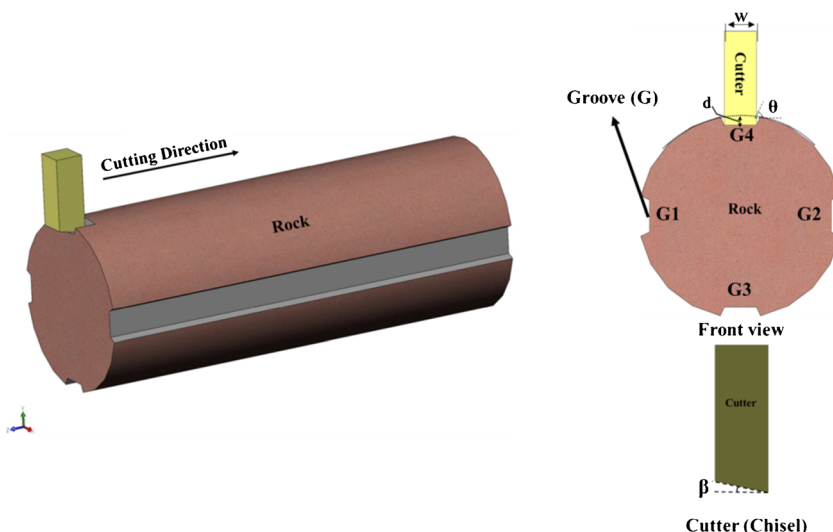
$$SE = \frac{F_C \times L}{V} \times 10^{-1} \quad (1 \text{ MJ/m}^3 = 0.278 \text{ kW-hr/m}^3) \quad (2)$$

where F_C is mean cutting force (kN), L is cutting length (cm), V is rock volume (cm^3) ($V = Y/D$), Y is yield (gr), and D is

Table 3 TC and the input parameters

Sample	Parameter							
	AW	AR	$N_0/(N_0 + N_1)$	$1/FF_0$	$N_1/(N_0 + N_1)$	AF_1	TC_1	TC
SQJ	1.00	2.36	0.81	1.49	0.19	0.90	1.56	1.56
SR1	0.27	2.87	0.79	1.30	0.21	1.05	1.59	0.41
SR2	0.29	2.42	0.80	1.48	0.20	0.80	1.55	0.53
SA1	0.35	2.33	0.90	1.50	0.10	0.66	1.53	0.64
SA2	0.28	2.14	0.85	1.37	0.15	1.03	1.47	0.39
M.K	0.29	2.82	0.61	1.32	0.39	0.62	1.53	0.45
CM1	0.40	2.89	0.58	1.40	0.42	1.03	2.00	0.85
CM2	0.38	2.84	0.73	1.27	0.27	1.00	1.85	0.73
SK	0.3	2.67	0.73	1.55	0.27	0.77	1.68	0.51
AK	1.00	2.48	0.80	1.31	0.20	1.12	1.42	1.42
AT	0.30	2.66	0.81	1.45	0.19	0.97	1.56	0.47

Fig. 3 A sketch of the chisel tool and core cutting test; rake angle = 0°, clearance angle = 12°, tip width = 12 mm



Density (gr/cm³).

Results of the laboratory tests of rock specimens including intact rock physical and mechanical properties, textural coefficient, and cutting output data are summarized in Table 4. As can be followed from the table, four rock specimens namely SQJ, SA₁, SA₂, and AK having UCS > 80 MPa were excluded from the list of cutting test. So, the F_c and SE values of these rock specimens are missed in the table.

Experimental results and discussion

Rock physical and mechanical properties

The bivariate correlations of CAI and TC with rock physical and mechanical properties are investigated in this section. Figure 5a shows the correlation between CAI and UCS. As seen, there is a linear correlation between these two parameters with coefficient of determination (R^2) equal to 0.77. Similar relationships between UCS and CAI were previously reported in other researches (e.g., by Al-Ameen and Waller 1994; Tiryaki and Dikmen 2006). Figure 5b shows the correlation of CAI with the porosity. As seen, a nonlinear inverse

correlation is observed, which is in good agreement with the findings reported by Abu Bakar et al. (2016).

The correlation between the CAI and TC is shown in Fig. 5c. As seen, these two parameters are weakly correlated ($R^2 = 0.27$). It can be revealed that the grain geometry is not the only effective parameter on rock abrasivity and the CAI is more dependent on grain hardness and the quality of cement or matrix. Ersoy and Waller (1995) stated this and noted that the CAI is very dependent to the minerals and degree of cementation. They reported a coefficient of determination of 0.50 between CAI and TC. Figure 5d shows the weak correlation between porosity and texture coefficient. As seen, these two parameters are completely independent of each other, indicating that the porosity is not a valid index to describe the texture coefficient of the rock.

Likewise, Figure 5 e and f show a weak correlation of TC with UCS and BTS, respectively. This is contrary to findings of Howarth and Rowlands (1987) who found good correlations between rock strength properties and texture coefficient in specimens taken from three different rock types (sandstone, marble and igneous rocks).

The weak correlations between the UCS, BTS, and TC in this study may be due to the fact that the texture coefficient does not include the significant petrographic parameters of

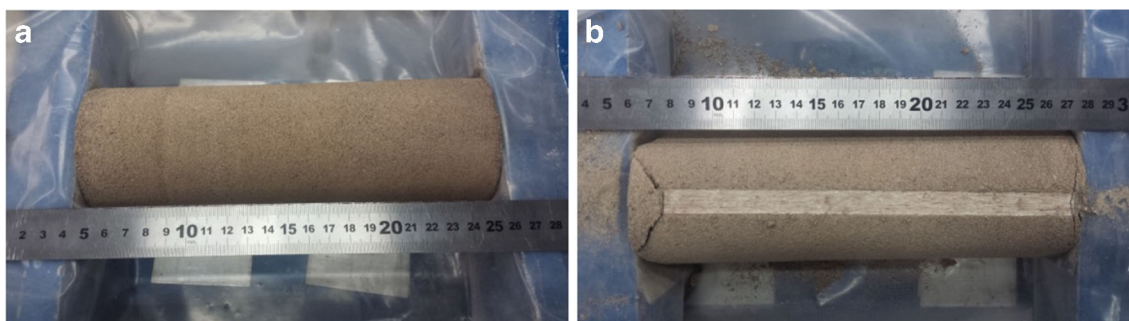


Fig. 4 Sample in the vise **a** before and **b** after cutting trial; core specimen: Upper Red Qom sandstone (SR2); cutting depth: 2 mm

Table 4 Results of the experimental data

Sample	Parameter								
	UCS (MPa)	BTS (MPa)	Porosity (%)	Density _{dry} (gr/cm ³)	CAI	TC1	TC	F _{c, Mean} (N)	SE _{Mean} (MJ / m ³)
SQJ	146.0	15.7	3.43	2.55	3.14	1.56	1.56	-	-
SR ₁	34.0	3.57	14.45	2.28	0.73	1.59	0.41	345	13.56
SR ₂	10.7	2.0	20.84	2.13	0.25	1.55	0.53	156	6.5
SA ₁	170.5	20.1	1.20	2.68	3.06	1.53	0.64	-	-
SA ₂	128.5	18.4	0.64	2.72	1.67	1.47	0.39	-	-
MK	21.6	3.25	20.27	2.17	0.23	1.53	0.45	305	10.68
CM ₁	47.5	3.7	15.28	2.17	1.34	2.00	0.85	758	25.27
CM ₂	66	4.5	9.20	2.26	2.75	1.85	0.73	989	31.56
AK	146.0	15.7	3.58	2.58	1.66	1.42	1.42	-	-
SK	53.3	10.4	2.21	2.6	1.91	1.68	0.51	766	32.26
AT	56.1	8.0	9.73	2.28	1.45	1.56	0.47	843	22.4

UCS, uniaxial compressive strength; BTS, Brazilian tensile strength; CAI, Cerchar abrasivity index; TC1, texture coefficient without exert W; TC, texture coefficient; F_{cMean}, mean cutting force; SE, specific energy

Fig. 5 Correlation between different rock properties. CAI: Cerchar Abrasivity Index; UCS: Uniaxial compressive strength; TC: Texture coefficient; BTS: Brazilian tensile strength

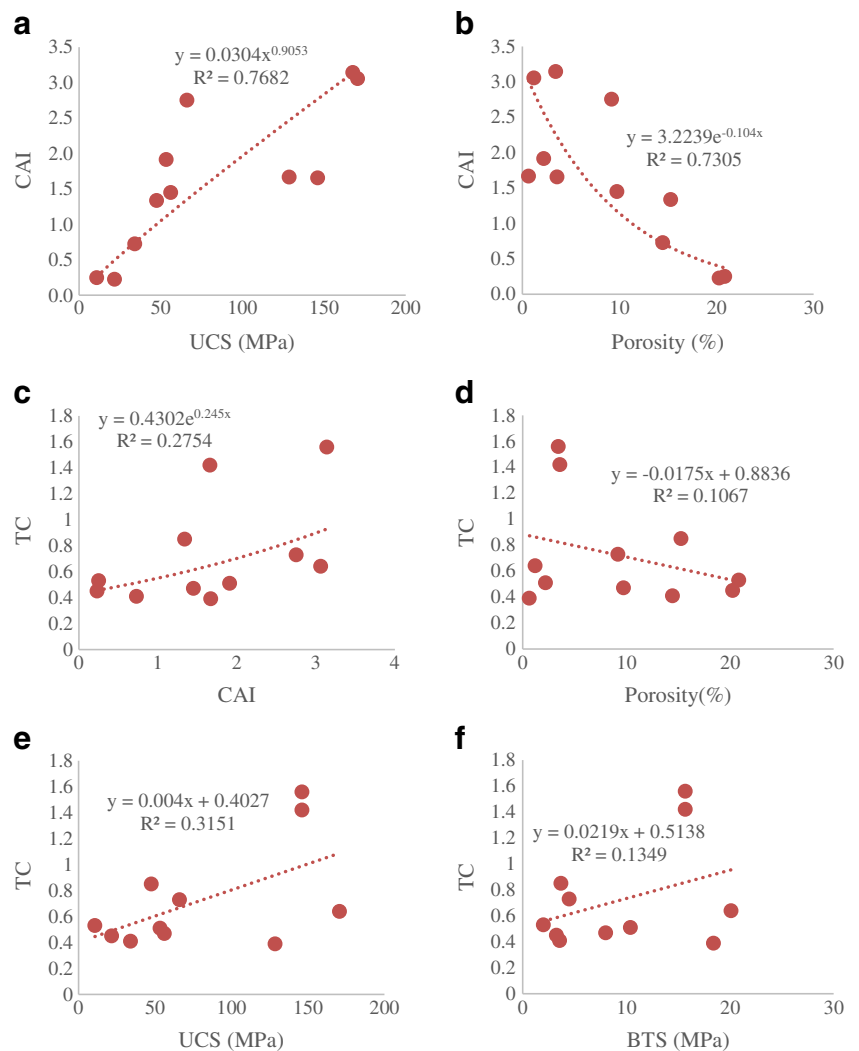
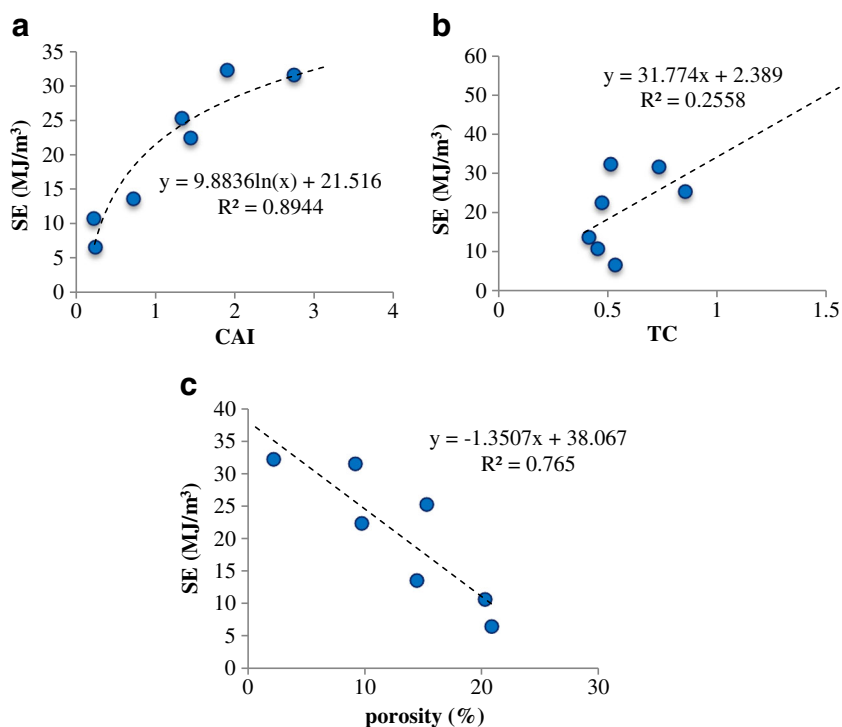


Fig. 6 Relationship of three rock microscale parameters with specific energy. SE: Specific energy; CAI: Cerchar Abrasivity Index; TC: Texture coefficient



porosity and mineralogical composition, as noted by Azzoni et al. (1996). Making reference to the experimental results, they concluded that TC could not be used to describe the rock mechanical properties and suggested that significant petrographic parameters of mineralogical composition to be added to the components of TC.

Microscale parameters and specific energy

The relationship of three microscale intact rock properties including porosity, texture coefficient, and CAI with specific energy obtained from core cutting tests is illustrated in Fig. 6. Very low to medium strength rock specimens were selected to describe the cuttability based on rock microscale parameters.

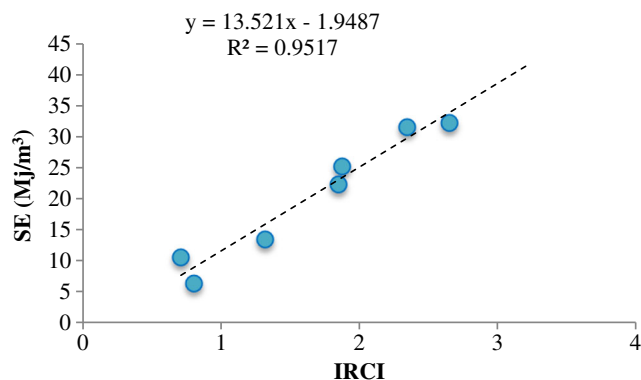


Fig. 7 Relationship between intact rock cuttability index and specific energy. SE: Specific energy; IRCI: Intact rock cuttability index

As seen in the figure, the relationship of SE with CAI and porosity is almost meaningful, but there is no meaningful relationship with TC. SE shows the closest relationship with CAI as SE increases in a logarithmic trend with increasing CAI (Fig. 6a).

Figure 6b illustrates the relationship between texture coefficient and specific energy. As seen, there is a weak correlation between TC and SE ($R^2 = 0.25$). The influence of textural properties on rock cuttability and the relationship between SE and TC are inconsistent with those of the results of small-scale rock cutting experiments reported by Ozturk et al. (2004) and Tumac et al. (2018).

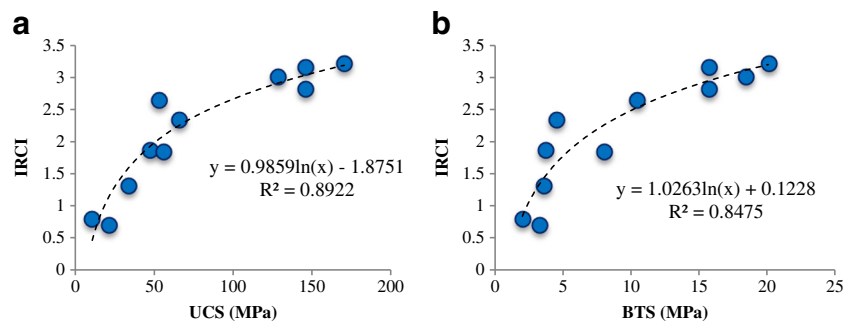
In Fig. 6c, the relationship between porosity and specific energy was investigated. As seen, there is a good linear reverse relationship between porosity and SE ($R^2 = 0.76$), clearly indicating the role of porosity in increasing rock cuttability. A similar linear relationship between porosity and SE with a close coefficient of determination was observed by Tiryaki and Dikmen (2006).

The influence of CAI, TC, and porosity on the cuttability of rock was investigated through bivariate correlation analysis. According to the results obtained from these analyses and also those of the literature, it is revealed that the rock cuttability is a complex index that requires more than one single property of the intact rock to be estimated reliably.

Intact rock cuttability index

In this study, intact rock cuttability index (IRCI) is introduced incorporating three rock microscale parameters including

Fig. 8 IRCI variation with **a** UCS and **b** BTS. IRCI: Intact rock cuttability index; UCS: uniaxial compressive strength; IRCI: Intact rock cuttability index; BTS: Brazilian tensile strength



abrasivity, texture coefficient, and porosity. The experimental method of measuring the three rock properties is convenient and repeatable with ease of preparation, and amenable to be performed on rock core samples, as suggested by Fowell and Johnson (1991) to be taken into consideration when selecting the input parameters for developing rock cuttability empirical models.

The intact rock consists of *mineral grains (materials)*, *cement or matrix*, and *pores*. TC representing the geometric features of the grains as well as the matrix space can be obtained from a photograph of a rock thin section. Meanwhile, the pore structure is not included in TC. So, the porosity is selected to express the pore volume in thin section analysis. Also, CAI represents the abrasivity and surface hardness of the rock and can be determined directly from the Cerchar test. Moreover, in this test, the steel pin is scratched over the rock surface as the chisel tool does over the rock in the both laboratory and field.

In order to incorporate the effect of three properties of intact rock, the suggested rock cuttability index is defined as follows:

$$IRCI = \log \left[\frac{1000(CAI \times TC)}{n} \right] \quad (3)$$

where IRCI is intact rock cuttability index, CAI is Cerchar abrasivity index, TC is texture coefficient, and n is porosity (%).

Figure 7 shows the relationship between IRCI and SE obtained from linear rock cutting test on seven rock specimens. It can be followed from the figure that there exists a strong correlation between SE and intact rock cuttability index. The coefficient of determination from SE versus IRCI relationship is higher than those of CAI, TC, and porosity against SE. This indicates that the multi-variable rock cuttability index provides more reliable estimation for cutting performance compared with a single rock parameter.

Also, the correlations of IRCI with UCS and BTS are shown in Fig. 8. As seen, rock strength parameters are strongly correlated with intact rock cuttability index.

IRCI is dependent on three microscale intact rock parameters requiring small-scale rock samples to be determined (e.g., as small as the disc specimen required for BTS test). This is very important in reducing the costs and difficulties related with sampling, sample transportation, and preparation and experiments. However, IRCI was suggested based on limited data such as few rock samples, low depth of cut, and fixed cutter geometry. It needs additional data to be checked for more rock specimens in a wider range of cutting and cutter geometries.

Conclusions

Rock specimens taken from different construction sites were subjected to mechanical tests including uniaxial compressive and Brazilian tensile strength and Cerchar abrasivity index. Also, texture coefficient, porosity, and dry density as physical characteristics were obtained.

Linear cutting tests with a chisel pick were conducted on very low to medium strength rock samples in order to determine specific energy. As an indicator of rock cutting efficiency, the SE was correlated with the intact rock cuttability index (IRCI). IRCI is a convenient multi-parameter cuttability index that takes into account concurrently the influence of three rock microscale properties, namely, rock texture coefficient (TC), Cerchar abrasivity index (CAI), and porosity (n). Moreover, it needs small pieces of rock sample as small as a sample for Brazilian test to be determined. The experimental results of cutting trials and correlation with proposed rock cuttability index showed that there is a strong logarithmic relationship between IRCI and specific energy. Also, it was also found that there are strong correlations between the suggested intact rock cuttability index and UCS and BTS.

Results of this study revealed that the rock cuttability can be estimated reliably using microscale rock properties, but further investigations are underway to extend the database by performing cutting tests on more rock samples and check the model validity for actual size cutting tools.

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