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Assessment of cerchar abrasivity test in anisotropic rocks

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Abstract. There have been developed a number of methods to assess the abrasivity of rock materials with the increased use of mechanized rock excavation. These methods range from determination of abrasive and hard mineral content using petrographic thin section analysis to weight loss or development of wear flat on a specified cutting tool. The Cerchar abrasivity index (CAI) test has been widely accepted for the assessment of rock abrasiveness. This test has been considered to provide a reliable indication of rock abrasiveness for isotropic rocks. However, a great amount of rocks in nature are anisotropic. Hence, viability assessment of Cerchar abrasivity test for the anisotropic rocks is investigated in this research. The relationship between CAI value and quartz content for the isotropic rocks is well known in literature. However, a correlation between EQ, F-Schimazek value, Rock Abrasivity Index (RAI) and CAI of anisotropic rocks such as phyllite was done first time in literature with this research. The results obtained with this research show F-Schimazek values and RAI values should be considered when determination of the abrasivity of anisotropic rocks instead of just using Cerchar scratch test.

Keywords: cerchar test; CAI of rocks; RAI of rocks; F-Schimazek index

1. Introduction

One of the major problems in rock cutting projects is the correct prediction of tool consumption. During the planning of project feasibility stage, expected tool consumption is a significant factor in the estimation of contractors' costs. The life of any cutter is possible to be estimated from the percentage of minerals having different Moh's hardness values. This is mostly determined with detailed petrographic analysis using a microscope. However, this is commonly determined by X-ray diffraction (XRD) for fine grained rock and soil. The higher the percentage of hard minerals means more abrasive soil or rock revealing shorter the cutter life. TBM performance is also influenced by many other textural features, such as grain size and shape, grain orientation (anisotropy); grain interlocking, microfractures and pores in addition to mineral composition (Efektari *et al.* 2018). Therefore, the use of Moh's hardness is preferred mainly for preliminary estimates of cutter wear (Ozdemir and Nilsen 1999, Su and Akcin 2005, Chang *et al.* 2017).

There are some well-known methods for estimating the abrasiveness of rocks in literature. The most commonly used are: 1) The Vickers test, giving the Vickers Hardness Number–VHN, 2) The Cerchar test, giving the Cerchar Abrasivity Index–CAI, 3) The LCPC abrasimeter test, giving the LCPC abrasivity index–ABR and 4) The NTNU abrasion test, giving the Abrasion Value-AV/AVS (Ozdemir and Nilsen 1999, Büchi *et al.* 1995, Ko *et al.* 2016). Another way of indirectly assess rock abrasiveness is throughout determination of geological and geotechnical parameters such as mineralogy, texture and rock strength, which are then correlated with CAI values (Thuro and Spaun 1996, Grahanbagh *et al.* 2011, Alber *et al.* 2013, Su and Akcin 2005, Fowel and Bakar 2007, Cheshomi and Moradhaseli 2017, Kahraman *et al.* 2018). One of the methods used tocorrelate these geological and geotechnical properties was defined by Schimazek (Schimazek and Knatz 1970) and is known F-value. In this paper special attention is given to the F-value. The F-value has shown a tendency to be linearly related to abrasive wear (Schimazek and Knatz 1970, 1976, Paschen 1980, Verhoef 1997). Certainly in Europe the F-value is used to assess abrasivity of rock, especially in coal mining and tunnelling. Voest-Alpine Bergtechnik uses graphs containing the F-value and unconfined compressive strength to predict the consumption of several types of tungsten carbide chisels (Gehring 1991). F values can be obtained from rock samples using the indirect Brazilian tensile strength test and by thin section analyses to obtain information on mineralogy and grain size. Hardness of minerals other than quartz are sometimes hard to find but it may be accounted for by expressing their hardness relative to that of Equivalent Quartz Content (EQC). Thus,

$$F=[EQC \times \emptyset \times \sigma t]/100 \quad (1)$$

F is the Schimazek's abrasiveness factor in N/mm, EQC is the equivalent quartz content or any other equivalent mineral and ø stands for the average quartz grain size in mm. F-Schimazek's values have a linear relationship with the abrasiveness of the rock (Peter 1993). That's mean the higher the F-Schimazek's value, the more abrasive rock and vice versa. The classification of abrasiveness for rocks done by using F-Schimazek values was proposed by Arthur (1996), (Table 1).

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Table 1 The classification of abrasiveness for rock materials (Arthur 1996)

Nomenclature	Class	F-Schimazek's Value
Extremely abrasive	1	> 11
Very abrasive	2	5 - 11
Moderately abrasive	3	2 - 5
Slightly abrasive	4	0.5 -2
Non abresive	5	< 0.5

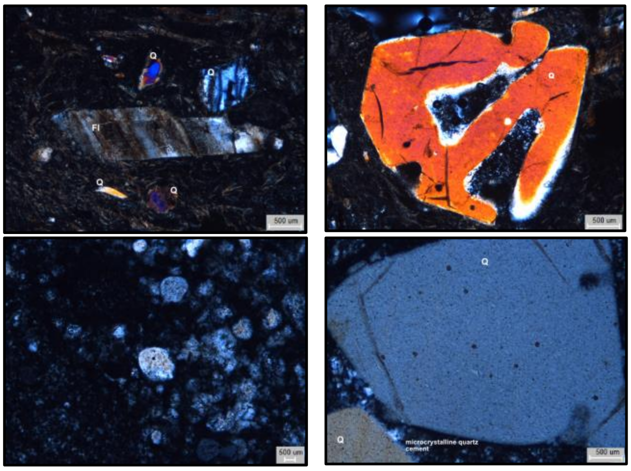
There are numerous discrepancies associated with the test which have to be addressed to make the test repeatable and reliable and to minimize the differences in measured CAI values by different laboratories. Various testing results from different laboratories have been studied by Rostami (2005) and Rostami *et al.* (2005). As it stands the Cerchar test has become a standard test of rock abrasivity for various applications such as use of Tunnel Boring Machines (TBM), roadheaders, and generally in tunneling industry. Therefore, variation in test results could cause variation in estimated cost of projects. Thus, there must be used a standard testing procedure for this test or alternatively, must be introduced a new test that can be used and inherently has less variation and can produce more reliable/repeatable results. The discrepancies in test results would be classified into two categories in general: 1) The issues related to the lack of standard until recently for the Cerchar test revealed experience, and judgment, which result outcomes different. 2) Other problems associated with intrinsic shortcomings of the test such as scale of the test, as well as the inconsistency of the pins, and impacts of variations in the rock sample (heterogenity, surface conditions) or the stylus that could result in errors in measurement (Grahanbagh *et al.* 2011).

Anisotropic rocks having bedding planes, gradation, banding, schistosity, etc., should be given special attention with respect to scratch directions (Alber *et al.* 2013). The location and direction of testing in any sample should be selected to represent the dominant mineralogy and texture of the rock sample observed in macroscopic samples (Alber *et al.* 2013). In order to obtain the relation between CAI and mineral composition of natural rocks, the contribution of each mineral to the CAI is needed. As quartz is, with only a few exceptions, the most abrasive rock forming mineral a relative scale of abrasivity with 100% corresponding to a CAI of 6.0 (= 100% quartz equivalence) can be set up.

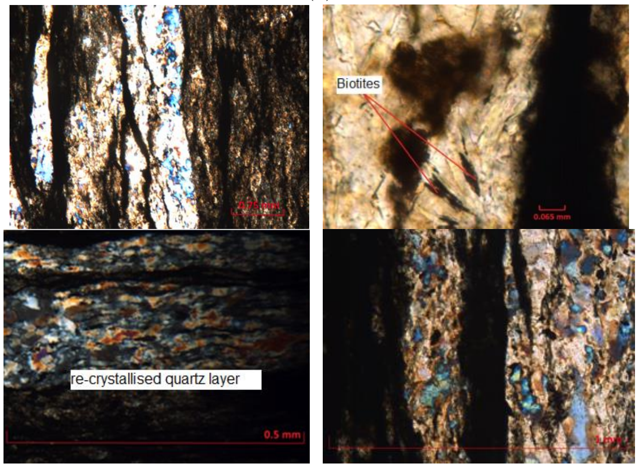
The "Rock Abrasivity Index" (RAI) introduced in 2002 represents an enhancement of the Equivalent Quartz Content (EQC). The RAI is calculated by multiplying a rock´s UCS and EQC. The RAI is applicable mainly to hard rock but also suitable to weak rocks. The RAI value is calculated for relevant rock types by multiplying the rock's Unconfined Compressive Strength (UCS) and Equivalent Quartz Content (EQC) (Plinninger 2010).

2. Tested rocks and experiments

Tuff and phyllite are typical anisotropic rock types in Brisbane Australia. Tests described herein were carried out



(a)



(b)

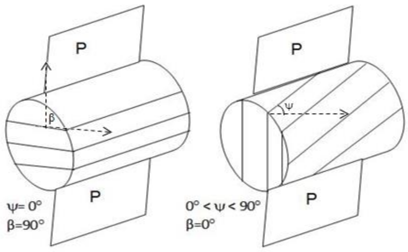
Fig. 1 (a) Photomicrograph of Feldspar (Fl) and Quartz (Q) mineral, and Quartz (Q) mineral in microcrystalline quartz and primary cryptocrystalline cement and (b) euhedral biotite grains showing some weathering and iron oxides liberation and recrystallised Quartz layer

on phyllite with clear white–black foliations, and tuff (Fig. 1). The phyllite samples are strongly foliated type phyllites with aphanitic and the foliationa are clear due to the layers of platy minerals (mainly biotite) interleaved with quartz rich layers. Tuff samples are composed largely of quartz and K-feldspar, with small amounts of siderite (Fe-carbonate) and zeolite minerals. In general, quartz and feldspar minerals are embedded separately in primary silica cryptocrystalline cement without interlocking. The mineral composition is primarily Quartz (crystals, quartz veins and recrystallised small grains), biotite and iron oxides, with muscovite, feldspars and garnets as secondary minerals. Cryptocrystalline texture in igneous rocks is a very fine aggregate of crystals, and in minerals means the individual crystals are too fine to be distinguished even under a petrological microscope. According to thin-section analysis, secondary carbonate cement replacing primary silica cryptocrystalline cement was observed (Fig. 1). Quartz is the most common mineral and comprises 54% of total composition. Biotite comprises 42% of total mineral composition. This mean value encompass iron oxides, as most of biotite are weathered and covered by iron oxides.

(a)

(b)

Fig. 2 (a) Phyllite and (b) tuff specimens



(a)

(b)

Fig. 3 (a) The angles Ψ and β and (b) some cored phylitte specimens

Quartz mainly occurs as equant or subhedral crystals. Biotites occurs as euhedral or irregular grains and show heavy weathering releasing iron oxides that are spread all over the slide. On the other hand, phyllite rock is a strongly foliated phyllite, aphanitic, with the foliation given by the presence of layers of platy minerals (mainly biotite), interleaved with quartz rich layers (Fig. 1(b)). Mineralogy is mainly composed by Quartz (crystals, quartz veins and recrystallised small grains), biotite and iron oxides, with muscovite, feldspars and garnets as accessories minerals. Quartz mainly occurs as equant or subhedral crystals. Biotites occurs as euhedral or irregular grains and show heavy weathering releasing iron oxides that are spread all over the slide (Fig. 1(b)).

Cerchar, indirect Brazilian Tensile Strength (BTS) and mode I (tensile) fracture toughness tests were conducted on

Fig. 4 West type Cerchar tester

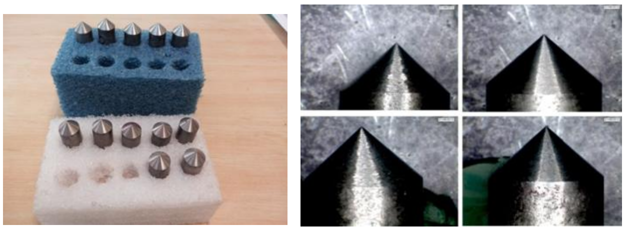


Fig. 5 Sharpened steel conical tips before testing

specimens prepared from tuff and phyllite core samples (Fig. 2).

The Brazilian Tensile Strength (BTS) sample preparation and testing procedure conformed to the requirements of the ISRM (ISRM 2007). The core samples were trimmed to form disc specimens 52 mm in diameter and 26 mm in thickness, to give a thickness to diameter ratio of 0.5. For the static BTS loading tests, ISRM (2007) suggests that the load be applied via two steel loading jaws in contact with a disc-shaped rock specimen, with the two steel loading jaws designed to make contact with the specimen at diametrically opposed surfaces over an arc of contact of approximately 10° at failure. The static load was applied by a stiff hydraulic Instron loading frame, with a loading rate of 200 N/s applied to the standard loading jaws, as suggested by the ISRM (2007). The experimental arrangement for the BTS tests is illustrated in Fig. 2 with respect to the orientation of the foliation planes. The foliation planes were found to be the true planes of weakness, characterised by reduced cohesive and reduced tensile strength. The the angle between the sample axis and the structural plane angle is defined as orientation angle Ψ and the angle between the loading direction and structural plane is defined as the foliation-loading angle (β) (Fig. 3).

As described before the Cerchar Abrasivity Index (CAI) is a measurement of the wear on a steel pin scratched five times over a rough rock surface. Two types of testing devices are in use today: (i) the original “Cerchar apparatus”, according to Cerchar (1986), and (ii) the “West apparatus”, according to West (1989), which was adopted herein (Fig. 4).

As recommended by West (1989), the steel pins are made from 200 kgf/mm^2 steel with 54-56 Rockwell Hardness. Special care was taken when re-sharpening the used testing pins. The sharpened tips of steel pins before testing are shown in Fig. 5.

3. Experimental results

The BTS tests were carried out in order to determine the tensile strength of specimens in directions relative to the planes of schistosity, ranging from 0° to 90°. 2-3 specimens were tested for each orientation. The BTS test results are given in Table 3. In general, a tensile failure crack at the centre of the disc specimens were obtained with the loading of isotropic disc specimens by using Brazilian jaws whereas those expected central tensile cracks were not obtained with the anisotropic phyllite disc specimens (Fig. 6). Mixed mode fracturing (tensile and shear) was mostly observed in certain cases. Two major modes of failure were observed: (i) tensile splitting along the loaded diameter which was the dominant mode of failure when β was between 0° and 30°, (ii) mixed mode fracturing which is tensile splitting and shear, along the layers with or without branching when 45°<β< 90° and 30°< ψ <45°.

The minimum failure load is obtained with the disc specimens having orientation and foliation-loading angles are zero, ψ=0° and β=0° respectively. Needless to say, the maximum failure load and the tensile strength are affected significantly by the existence of foliation or schistose planes perpendicular or parallel to the direction of maximum tensile stress.Second series of the tests were Cerchar abrasivity tests. Cerchar test is based on a steel needle with defined geometry and quality that is scratched over 10mm over a rock surface under static load of 70N. The CAI is then calculated from the measured diameter of the resulting wear flat on the testing needle (Alber *et al.* 2013). Fig. 7 and Fig. 8 show pins during testing and some tested specimens.

After cleaning any rock debris from the conical tips, the wear flat was measured using the light microscope with a magnification of 50x. The worn steel tips after testing of the tuff and phyllite specimens are shown in Fig. 9.

Fig. 6 Some tested BIT phyllite specimens

Fig. 7 Steel pins before scratching

Fig. 8 Tested Cerchar tuff and phyllite specimens

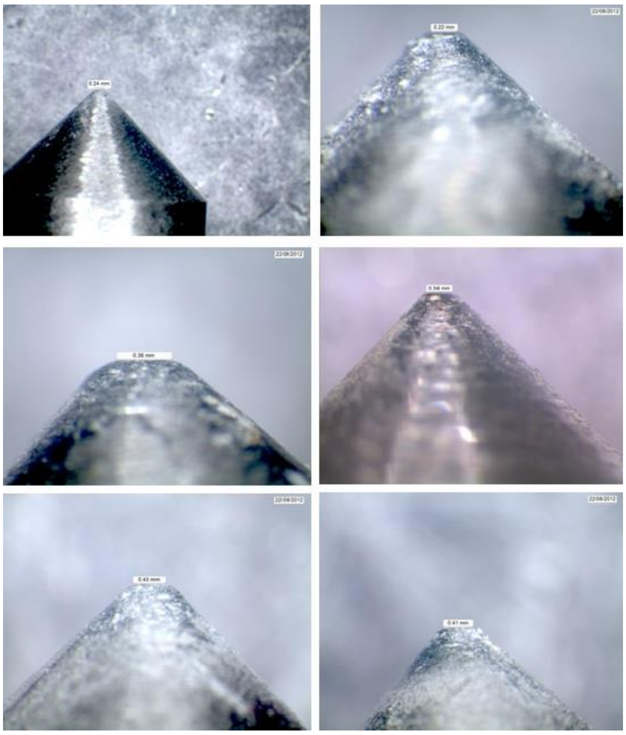


Fig. 9 Worn steel tips after Cerchar testing

The arithmetic average of five scratches was empirically found to give a representative Cerchar Abrasivity Index on rock samples with less than one millimetre grain size. The test results are given in Table 3. The CAI values of the three tuff samples were found to be between 2.3 and 3.5. On the other hand, the CAI values of the phyllite samples were found to be between 3.1 and 4.2 (Table 2). The tuff samples are classified as ‘very abrasive rock’ whereas phyllite samples are classified as ‘very abrasive’ to ‘extremely abrasive’ rocks according to Thuro and Kasling (2009). On the other hand, the tuff samples are classified as ‘medium abrasive rock’ whereas phyllite samples are classified as ‘moderately abrasive’ rocks according to Bieniawski *et al.* (2008).

3.1 Equivalent quartz content

Cerchar test was proposed for isotropic and homogenous

Table 2 Cerchar test results

Sample	Diameter of wear flat (mm)		
	First cut	Secnd cut	*CAI (Average of two readings)*
TF1 (Tuff)	0.24	0.22	2.3
TF2 (Tuff)	0.26	0.25	2.5
TF3 (Tuff)	0.36	0.34	3.5
TF4 (Tuff)	0.33	0.31	3.1
PH1 (Phyllite)	0.39 30° with axis of quartz seam	0.43	4.1
PH2 (Phyllite)	0.32 30° with axis of quartz seam	0.36	3.4
PH3 (Phyllite)	0.43 45° with axis of quartz seam	0.41	4.2
PH4 (Phyllite)	0.33 45° with axis of quartz seam	0.30	3.1
PH5 (Phyllite)	0.35 60° with axis of quartz seam	0.33	3.4
PH6 (Phyllite)	0.37 60° with axis of quartz seam	0.40	3.8
PH7 (Phyllite)	0.50 (0° with axis of quartz seam)	0.48 (90° with axis of quartz seam)	5
PH8 (Phyllite)	0.45	0.35 (90° with axis of quartz seam)	3.5 (not valid test)

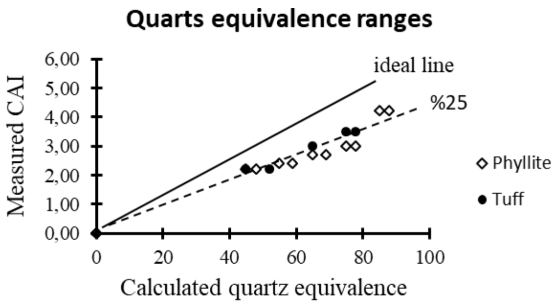


Fig. 10 Measured Cerchar Abrasivity Index (CAI) and calculated abrasivity (quarts equivalence) of tuff and phyllite samples

rock types. However, most abundant rock types on earth's crust such as sedimentary and metamorphic rocks are mostly anisotropic rocks. That's why, behaviour and wear properties of those kind of rocks are very important. In contrast to the West's proposal, the Equivalent Quartz Content (EQC) alone is not suited to interpret the abrasion values of the Cerchar scratch test. It is clear, that tool wear is predominantly a result of the mineral content harder than steel, especially quartz (Mohs hardness of 7). To include all minerals of a rock sample, the EQC has been determined in thin sections by modal analysis - meaning the entire mineral content referring to the abrasiveness or hardness of quartz. Therefore, each mineral amount is multiplied with its relative Rosiwal hardness to quartz (with quartz being 100%). The equivalent quartz contents of components to an EQC for a mixture of grain sizes can be done statistically. However, a more elegant method, which has been used successfully in this study, is the full analysis of a powdered sample with an X-ray diffractometer. If the mineralogical composition is known a theoretical CAI can be calculated with the quarts equivalence meaning the entire mineral content referring to the abrasiveness or hardness of quartz (Moradizadeh *et al.* 2016).

Measured CAI values and quartz equivalences calculated from the mineralogical composition of ten phyllite samples and five tuff samples are plotted (Fig. 10). If there were no other influencing factors, all samples should lie on a straight line going through zero and %100/6.0 quartz equivalence/CAI (ideal line). However, our test results are in -%20 to -%30 deviation range from the ideal line. This deviation is believed to be resulted due to the anisotropy.

One important point with the determination of EQC is ignoring the anisotropy and quartz seams in anisotropic rocks as those quartz seams increase the total quartz content abnormally considered with the total percentages of rock forming minerals in an anisotropic rock sample. That's why; another correlation between CAI, EQC and anisotropy planes of rocks is required to make Cerchar test validated for the anisotropic rocks.

4.2 F-Schimazek's value

The combination of the particle size with the quartz content and the tensile strength is useful for the estimation of bit wear and was introduced by Schimazek and Knatz (1970) as the wear coefficient. The following example shows that the prediction of the bit wear is not only dependent on the quartz content. Assume sandstone with a clayey matrix and fresh granite. Both materials might have a quartz content of 60°. However, there is no doubt that the bit wear in the sandstone is lower than in the granite. If only the quartz is taken into account the bit wear would be the same for each. The difference is only indicated, if the lower tensile strength and the smaller particle size of the sandstone are taken into consideration by using the wear coefficient (Natau *et al.* 1991). The rock abrasivity properties were also determined by using F-Schimazek's Value. The F-Schimazek value shows the abrasiveness of rock towards the tool or cutter wear that used in the excavation work. This index can be evaluated by using Eq. (1) proposed by Schimazek and Knatz (1970).

The phyllite is light grey in color with a few spotted of dark mineral. The grain size is medium-grained, ranging in the type of specimen from about 1 to 2 mm and well interlocked. The abrasiveness of those two rock types is determined by using F-Schimazek Value. The value represents the abrasiveness of material towards the tool or cutter wear that used in the drilling and hard rock cutting works. The index values given in Table 3 are calculated by using Eq. (1).

4.3 Rock abrasivity index (RAI)

A correlation between the Rock Abrasivity Index (RAI)

Table 3 F-Schimazek values of tuff and phyllite samples

Types of Rock	Tensile Strength, σ_t (MPa) (avr. of 3)		Quartz ((%) (aver. of 5)	Grain Size (mm)	F-Schimazek's Value	Nomencl.
Tuff	β (°)	σ_t (MPa)				
	0	5.2	55	0.8	2.3	Moderate abrasive
	30	7	64	0.7	3.1	Moderate abrasive
	45	8.5	73	0.8	4.5	Moderate abrasive
	60	9	79	0.7	5.0	Moderately abrasive
Phyllt.	β (°)	σ_t (MPa)				
	0	5.5	54	0.9	4.4	Moderate abrasive
	30	6	65	1.0	4.5	Moderate abrasive
	45	10	73	0.6	4.4	Moderate abrasive
	60	11	60	0.6	3.9	Moderate abrasive

Table 4 Calculated CAI values by using RAI

Tuff			Phyllite	
RAI	$CAI_{(RAI)}$		RAI	$CAI_{(RAI)}$
		β (°)		
30	2.79	0	22	2.52
32	2.86	30	31	2.82
29	2.76	45	36	2.97
35	2.94	60	29	2.76

and the widely used CAI are derived from a model test for the estimation of button bit wear (Schumacher 2004). Besides the graphical solution, Schumacher (2004) derived a practically useful square function as given in Eq. (2).

$$CAI = 0.9\,\sqrt[3]{RAI} \qquad (2)$$

where CAI = Cerchar Abrasivity Index; RAI = Rock Abrasivity Index. Table 4 gives the calculated CAI values by using the relationship between RAI and CAI.

4. Discussions

Various factors affect the abrasiveness of rocks. Particularly important factors effecting abrasivity of rocks are: (a) mineral composition, (b) the hardness of mineral constituents, (c) grain shape and size, (d) the type of matrix material and (e) physical properties of the rock including strength, hardness, toughness and anisotropy. It can be observed that the inter-relations between rock competency, hardness and abrasivity are all of importance. However, even very weak rocks can cause excessive wear and high costs with certain excavation modes such as bucket wheel excavation or drag line (Atkinson and Cassapi 1984; Kasturi 1984). That's why; determination of rock abrasivity should be done by including those factors. Geotechnical indexes such as F-Schimazek index, Equivalent Quartz Content (EQC) and RAI index values are found very important to criticize the abrasivity class obtained with the CAI values in this research. Nevertheless comparison between different geotechnical wear prediction procedures show that simple model tests like Cerchar test have some weaknesses that give rise to supposition that even more and better data sets about rock heterogeneity and anisotropy (Thuro and Spaun 1996, Grahanbagh *et al.* 2011, Alber *et al.* 2013). CAI values are counted in the determination of cutting efficiency in many engineering applications. However, effect of anisotropy or extra attention on this test is ignored in determination of CAI values of rocks. Of course, rock properties and drilling rates are highly dependent on the orientation of weakness planes related to the direction of testing or drilling. This has been discussed in detail by Thuro and Spaun (1996).

When using UCS and BTI core parameters, the RAI takes into account the content of abrasive minerals (which is especially relevant for abrasive wear) and the strength of the rock (which has found to be relevant for both, abrasive wear and wear due to breaking of tool parts (Plinninger et al, 2003). The RAI value is should be considered as a geotechnical wear index, derived from laboratory tests from small scale samples and mineral/rock scale investigations. That's why; more extensive techniques including both intact rock strength parameters and content of abrasive minerals should be generated to determine a realistic abrasivity index of anisotropic rocks.

Anisotropy is a characteristic of intact foliated metamorphic rocks (gneisses, phyllites and schists), and intact stratified or bedded sedimentary rocks (coal, shales, sandstones, siltstones, limestones, etc.). Rock mass anisotropy in such volcanic formations and in sedimentary formations at a larger scale, is found in consisting of alternating layers or beds of different rock types and in rock formations with one or several regularly-spaced joint sets. Although mechanical properties allow prediction of rock cutting performance precisely, geological influences are even more decisive for cuttability as well as for the bit life. There are several geological influences though only some can be mentioned here: 1) anisotropy - orientation of discontinuities related to the direction of testing or drilling, 2) spacing of discontinuities, 3) mineral composition - equivalent quartz content and 4) pore volume - porosity of the micro fabric. Of course, cutting performances in any tunnel boring are also highly dependent on the orientation of weakness planes related to the direction of testing or drilling. For example, when the direction of drilling is at right angles to the orientation of foliation, rock material is compressed at right angles but sheared parallel to it. Although cracks in general develop radial to compression, the cracks parallel to the bottom of the borehole cause chipping. That's why; determination the abrasivity of anisotropic rocks should be done by considering the change of abrasivity and strength of rock material depending on the orientation plane (Thuro and Spaun 1996, Grahanbagh *et al.* 2011, Alber *et al.* 2013).

Table 5 shows various abrasivity indexes found with this research for the Tuff and phyllite specimens. According to Thuro and Kasling (2009), tuff is classified as 'Very abrasive rock' when considered the given $CAI_{(Cerchar)}$ values

Table 5 Various abrasivity indexes for Tuff and phyllite rocks

CAI (Cerchar)	RAI	CAI (RAI)	F-Schimazaek		RAI	CAI (RAI)	CAI (Cerchar)	F-Schimazaek
2.3	30	2.79	2.3	β(°)				
2.5	32	2.86	3.1	0 (qrtz seam)	22	2.52	5	4.4
3.5	29	2.76	4.5	30	31	2.82	3.75	4.5
3.1	35	2.94	5	45	36	2.97	3.65	3.9
				60-90	29	2.76	3.60	4.5

in Table 7. Anisotropic phyllite is classified as 'Very abrasive' up to 30° plane orientation and 'Extremely abrasive' up to 60° orientation plane when considered the same classification system. On the other hand, tuff is classified as 'moderately abrasive and phyllite is classified as 'Just abrasive' rock when Bieniawski classification is considered (Bieniawski *et al.* 2008). This result also shows there is a serious discrepancy between the proposed Cerchar classification systems in literature. According to the F-Schimazek values given in previous section, tuff and phyllite are classified as 'Moderately abrasive rock'. On the other hand, both tuff and phyllite are classified between 'Moderately abrasive' and 'Abrasive rock' when considered the RAI classification system. It seems that results of both F-Schimazek and RAI rock abrasivity classification systems confirm each other more compared with the CAI classification tables proposed in literature.

After all, it can be concluded CAI values obtained with the Cerchar scratch test are needed to be related with some other abrasivity index values and/or rock petrographic parameters to represent the precise abrasivity class of anisotropic rocks (Saeidi *et al.* 2015). For example, Fowel and Bakar (2007) established a correlation between CAI, grain size and EQC as

$$CAI = 0.127xEQC - 7.45xGrSize + 2.008 \quad (3)$$

where CAI=Cerchar abrasivity index, EQC=Equivalent quarts content (%) and GrSize=Grain size. Both rock types are classified as 'Very abrasive rock' according to Cerchar scratch test values and values obtained with the Eq. (3). However, both rocks are catagorized as 'Modarately hard rock' when UCS values of both rocks are taken into consideration in terms of cuttability of rocks. It can be concluded from those results RAI and F-Schimazek values almost confirm each other when considered the mechanical strength values of anisotropic rocks and EQC. On the orher hand, CAI values obtained with the Cerchar scratch test are in good agreement with the CAI values calculated by using the EQC values and grain size of hard minerals instead of mechanical strength values of rocks. In conclusion, this paper proposes that F-Schimazek values and RAI index values should be considered when determining the abrasivity of anisotropic rocks up to 60° plane of anisotrophy.

5. Conclusions

The main conclusion drawn from this study is the abrasiveness of a rock sample based on F-Schimazek's Value and RAI is strongly influenced by the grain size, tensile strength depending on anisotropy and the percentage of quartz/hard minerals consisted in the rock samples. On the other hand, abrasiveness of a rock sample determined by Cerchar scratch test is strongly influenced by the cutting direction with the axis of anisotropy and scratch length. The results showed the Cerchar tests conducted on anisotropic tuff and phyllite samples have higher CAI values than the expected abrasivity values of those rocks in literature due to the quartz seams. Moreover, during scratching normal to the quartz seams (90° with the axis of quartz seam), some phyllite specimens were split into sheets through the quartz seam. That's why; F-Schimazek values and RAI index values should be considered to determine the abrasivity class of anisotropic rocks up to 60° plane of anisotropy with the axis of attack. Moreover, CAI values obtained with the Cerchar scratch test are needed to be related with some other abrasivity index values and/or rock petrographic parameters to represent the precise abrasivity class of anisotropic rocks.

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