

Study of Dominant Factors Affecting Cerchar Abrasivity Index

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Abstract The Cerchar abrasion index is commonly used to represent rock abrasion for estimation of bit life and wear in various mining and tunneling applications. Although the test is simple and fast, there are some discrepancies in the test results related to the equipment used, condition of the rock surface, operator skills, and procedures used in conducting and measuring the wear surface. This paper focuses on the background of the test and examines the influence of various parameters on Cerchar testing including pin hardness, surface condition of specimens, petrographical and geomechanical properties, test speed, applied load, and method of measuring wear surface. Results of Cerchar tests on a set of rock specimens performed at different laboratories are presented to examine repeatability of the tests. In addition, the preliminary results of testing with a new device as a potential alternative testing system for rock abrasivity measurement are discussed.

Keywords Cerchar test · Cerchar abrasivity index · Bit life · Wear · Rock abrasion

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1 Introduction

Abrasion controls the wear life of cutting tools in any rock excavation operation from small holes drilled for blasting large diameter tunnels bored by the tunnel boring machines (TBMs). Various rock abrasion measures have been introduced throughout the years to allow the engineers to estimate tool life. As the wear life of the rock cutting tools often has a linear relationship with the measured rock abrasion, any variation in the measurements has a direct and proportional impact on the estimated tool life, operational delays, and related costs. Therefore, the accuracy and repeatability of the test used for quantification of rock abrasion has some bearing on the project schedule and cost. The Cerchar abrasivity test is one of the tests that is frequently used on a worldwide basis for abrasivity assessment of rocks and wear prediction. Due to variations of the test results, reliable and comparable testing results are rarely available. This has been the reason for seeking other rock abrasion testing such as the Laboratoire Central des Ponts et Chaussées (LCPC) abrasivity test and abrasion value cutter steel (AVS) test, which have become more and more common internationally for rock and soil testing. A unified abrasivity classification for the Cerchar abrasivity index (CAI) and the LCPC abrasivity coefficient has been studied by Thuro et al. (2007), which is based on the classification of Cerchar (1986). This system has already been used in construction practice with seemingly successful results (Käsling and Thuro 2010). The AVS test, originally developed by NTNU, has been used in numerous major international underground projects and the NTNU/SINTEF database does currently contain results from 1,590 tested samples (Dahl et al. 2012) However, the Cerchar test remains the most commonly used test for rock

abrasion due to its simplicity and as such, the parameters influencing the measured results are the subject of the current study.

The Cerchar Abrasivity Test has been introduced in the 1970s by the Centre d'Etudes et Recherches des Charbonages (CERCHAR) de France for abrasivity testing in coal bearing rocks in mining industries while gradually being adopted for application in tunneling industry (Alber 2008; Plinninger et al. 2004). While the test layout was described by Cerchar (1986), different setups are available for Cerchar testing. In general, they all consist of a vice holding the specimen while a hardened steel stylus with a 90° cone tip is scratched over the rock surface under constant load of 70 N. The scratch covers a distance of 10 mm. The testing device developed by Cerchar (1986) is illustrated in Fig. 1. Another apparatus designed by West (1989) is shown in Fig. 2. This apparatus is widely used in commercial and laboratory application.

Despite common use of the test, there are some discrepancies in the results which are mainly related to variations in the test procedures, equipment used for testing, the hardness of the pins used in testing, surface condition of the specimens, methods of measuring the wear flat (from top or side), and ultimately lack of understanding the influence of different testing parameters on the results (The wear flat is the blunting of the top of the steel pin after testing as it is shown in Fig. 11). While the original formal standard of the test was the French standard NF P 940-430-1 (Afnor 2000), recently an ASTM standard (D7625-10) for Cerchar testing has been issued. ISRM has, in addition,

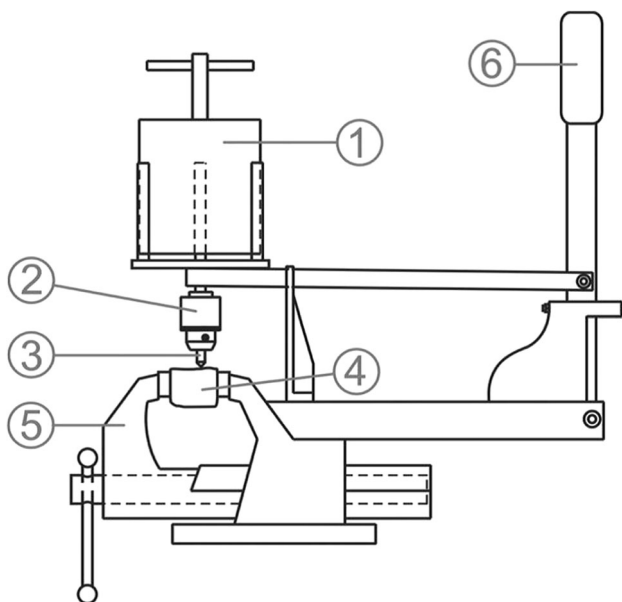


Fig. 1 Setup of a modified Cerchar testing device according to Cerchar (1986). 1 Weight, 2 pin chuck, 3 steel pin, 4 specimen, 5 vice, 6 hand lever

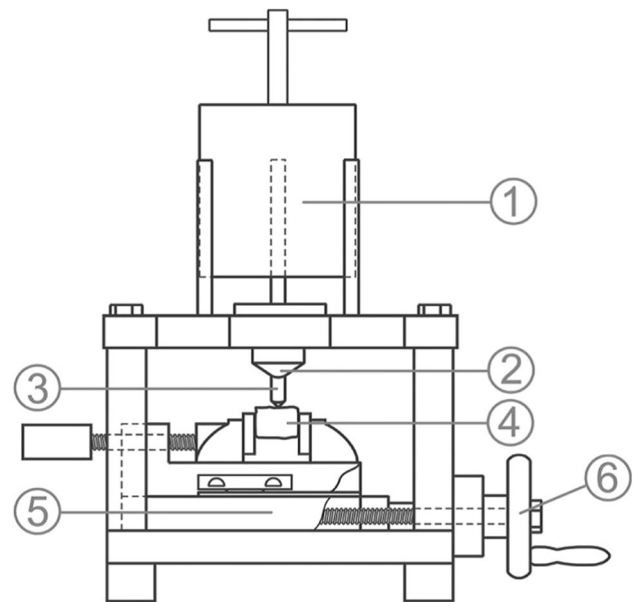


Fig. 2 Setup of a testing device according to West (1989). 1 Weight, 2 pin guide, 3 steel pin, 4 specimen, 5 vice sled, 6 hand crank

recently established a working group which currently is working on an ISRM standard for determination of the Cerchar abrasion index. Yet the availability of the standard does not preclude the spread in the test results as has been observed in practice.

2 Test Parameters

One of the most important aspects of any test is the repeatability of the results, which has been a point of discussion for the Cerchar Test. While West (1989) maintains that the test is repeatable for the same rock, Rostami et al. (2005) sent the exact same set of specimens to different laboratories and obtained different results. Differences in results were considered due to various equipment type, procedures, pin and surface types, and finally the measurement method. The study, which is discussed in this paper, can be considered as a continuation and complementary step to the research by Rostami et al. (2005). This section discusses the influence of various parameters on the test results. Following is a brief review of main testing parameters and their influence on the measured value of Cerchar that is being reported as the test results.

2.1 Pin Hardness

One of the main parameters in Cerchar testing is pin hardness, which has been a source of discrepancy. According to the French standard, the stylus must be made of steel, heat-treated to Rockwell hardness HRC 54/56

(Michalakopoulos et al. 2006). However, the steel used by different laboratories varies over a wide range (Plinninger et al. 2003). Some labs perform the tests with pins of hardness HRC 54/56, while others use a HRC 40 stylus and even softer ones (Alber 2008; Michalakopoulos et al. 2006; Plinninger et al. 2003; Suana and Peters 1982; Yarali et al. 2008; West 1989; Al-Ameen and Waller 1994). Stanford and Hagan (2009) performed a study on the influence of steel type and hardness on Cerchar test results. Their study involved testing seven different metal types heat-treated to the same hardness level and one steel type at nine different hardness levels. In their study, steel types refer to various grade, composition, etc., and steel hardnesses varied between HRC 50 and HRC 55. They used the steel types such as Silver Steel, H13, M340, CALMAX, SVERKER, 3, Rigor and S600. They performed the test using different steel types but with the same hardness and concluded that there was no significant difference between the results for steel of the same hardness irrespective of the type and treatment used to reach the desired hardness. According to Stanford and Hagan, while steel type of the stylus was varied, the hardness was kept constant at a level between that specified by CERCHAR (1986) of 2,000 MPa and West (1989) of Rockwell Hardness C (HRC) 40. The actual hardness of the seven steel styli, which Stanford and Hagan studied, varied slightly between HRC 50 and 55 being equivalent to a yield strength ranging between 1,606 and 1,889 MPa. This indicates that selection of the stylus for Cerchar testing based on steel type alone is unlikely to have any significant effect on the measured CAI. They also studied the same steel with different hardness and concluded that CAI decreases linearly with increased pin hardness. Michalakopoulos et al. (2006) also came up with a linear relation between CAI40 and CAI55.

2.2 Scratching Distance

According to the original Cerchar document, the scratching distance should be 10 mm. Studies showed that about 70 % of the stylus wear occurs in the first millimeter of the testing length and about 85 % of the CAI is achieved after 2 mm. Only 15 % of the CAI is attributed to the last 8 mm of the testing path (Plinninger et al. 2003; West 1989). Thus, one can conclude that variation of the length of the scratch within a small range does not alter the results significantly. However, a recent study by Hamzaban et al. (2013) shows that the amount of wear on the pin top that occurs along the scratch is a function of the hardness and strength of the specimen being tested. The measured size of the wear flat (or Cerchar index) along the scratch reached a constant value in soft to medium rock specimens, as compared to a gradual increase of the measured value on harder, more abrasive rocks. In other words, the size of the

measured wear flat increases with the length of the scratch in very abrasive specimens such as quartzite, hard and quartz-rich granitic rocks. This means that in measuring the Cerchar index for very abrasive rocks, the length of the scratch should be carefully watched, whereas in soft to medium specimens some variations of the scratching distance are tolerable. The best indicator for this phenomenon is the surface condition of the specimen, whereas in soft to medium specimens the test leaves a groove and in harder specimens, there is no penetration into the rock surface or groove, rather a metal streak can be observed.

2.3 Test Number

Cerchar suggested using 2–3 single tests for fine-grained, homogeneous rock specimens and five or more tests for specimens with grain sizes of more than 1 mm (Plinninger et al. 2003). West (1989) mentioned that five single tests should be representative and most researchers and commercial laboratories follow this recommendation (Plinninger et al. 2003; Yarali et al. 2008). Stanford and Hagan (2009) used seven styli and excluded highest and lowest outlier measurements from their calculation.

2.4 Stress

Alber (2008) studied the influence of in situ stress on Cerchar test results. He concluded that CAI increases under the presence of confining pressure around the specimen as

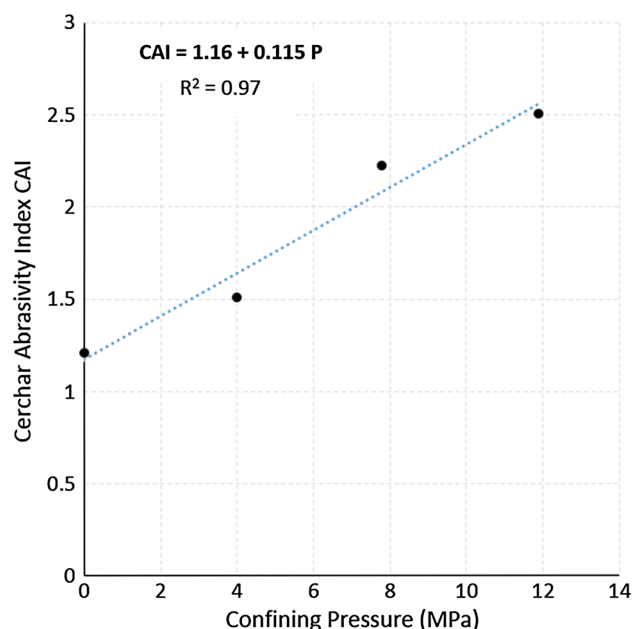


Fig. 3 CAI versus confining pressure, test results of one sandstone specimen (Alber 2008)

shown in Fig. 3. However, the lower the CAI value under ambient condition (with no confinement) the more pronounced the increase in CAI appears to be.

2.5 Surface Condition of the Rock Specimen

The original Cerchar test guidelines did not mention anything about the surface condition of the specimens. Some researchers have performed their tests on rough surfaces while others used sawn surfaces (Alber 2008; Suana and Peters 1982; Yarali et al. 2008; West 1989; Stanford and Hagan 2009). Al-Ameen and Waller (1994) mentioned that the surface finish has a minor effect on the results. In addition, Plinninger et al. (2003) confirmed this observation in the rocks with low CAI values. However, their research showed that CAI values in hard rocks are about 0.5 unit (or 0.05 mm) higher on rough surfaces as compared to sawn specimen surfaces. Rostami et al. (2005) also found a similar trend. The influence of the rock surface is rather important for the higher CAI values as can be seen in Fig. 4. Figure 5 shows that the CAI measured on a smooth, saw-cut surface is lower than the CAI measured by scratching the pin on the rough, freshly broken rock surface, as recommended in the French standard. Again a reliable conversion from a saw-cut surface CAI to a rough surface CAI and vice versa is difficult due to the high deviation, especially at high CAI values. Furthermore, the orientation of the test using anisotropic rocks and the precise reading of the wear flat of the steel pin are relevant for comprehensible results (Käsling and Thuro 2010).

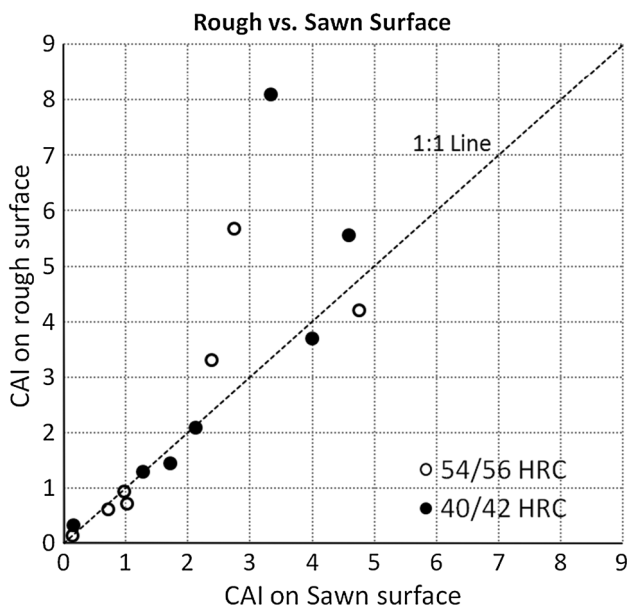


Fig. 4 Comparison of CAI testing of rough vs. sawn surface

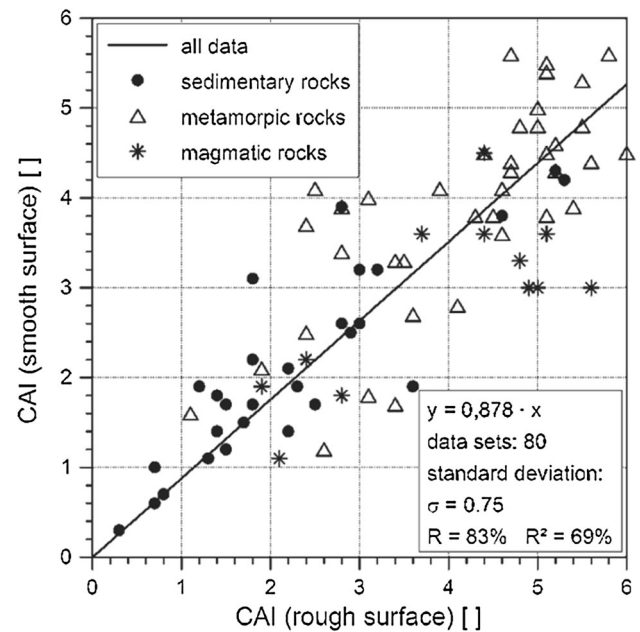


Fig. 5 Results of Cerchar abrasivity tests carried out on rough rock surfaces and smooth, saw-cut surfaces in Käsling and Thuro (2010)

2.6 Petrographical and Geomechanical Properties

West (1989); Suana and Peters (1982), and Yarali et al. (2008) mentioned that there is a good correlation between CAI and quartz content of the rock. Plinninger et al. (2003) stated that the combination of Young's modulus and the equivalent quartz content has a fair correlation with CAI value. The equivalent quartz content (Qeq) of coal measures rocks was determined using Rosiwall mineral abrasiveness ratio (Schimazek and Knatz 1970). The equivalent quartz percentage is estimated using 3 % of carbonates; 4 % of mica, chlorite, and clay; 33 % of feldspars; and 100 % of quartz of rock mineral content (Tamrock 1999). Al-Ameen and Waller (1994) implied that the rock strength has the most important effect on the CAI value. Alber (2008) could not obtain a significant correlation between CAI and quartz content/equivalent quartz content. He correlated the porosity of the rocks with increase in CAI per 1 MPa confining pressure and came up with a linear relationship, and then concluded that the CAI may be seen as a function of the rock porosity. In general, CAI seems to correlate well with rock strength (Uniaxial Compressive Strength) and average hardness of the constituent minerals as represented by quartz content or its equivalent. The same trend has been observed by Hamzaban et al. (2013) relative to the strength of the various specimens tested in their program.

2.7 Test Speed

The speed of the pin movement on the rock surface or test speed has also been considered as a source of variation in

the test results. West (1986) suggested performing the test in about 1 min. However, Alber (2008) and Yarali et al. (2008) carried out their tests in 1 s, while Michalakopoulos et al. (2006) performed their tests over 10 s. Plinninger et al. (2004) mentioned that the speed of tests does not affect the results much. Rostami et al. (2005) mentioned that in the labs using pins with the hardness of HRC 43, test results are generally higher at slower rates of movement.

2.8 Measuring Apparatus and Method

Cerchar recommends using a microscope to read the wear surface of the styli, but does not describe the procedure in detail (Al-Ameen and Waller 1994). West (1989) suggested that two orthogonal diameters should be measured and the mean value should be reported. He suggested using a microscope with magnification factor of 24×. Al-Ameen and Waller (1994) used a travelling microscope with the precision of $\pm 2 \mu\text{m}$, while Yarali et al. (2008) utilized a binocular microscope with magnification factor of 25×. Plinninger et al. (2003) suggested using a reflected light microscope with magnification factor of 50×. Rostami et al. (2005) introduced a technique to measure the flat surface diameter using a microscope viewing the stylus from the side and noted that the difficulties associated with viewing from the top could be reduced using the new measuring technique.

2.9 Applicability of the Test

West (1989) mentioned that the CAI test is suitable for most rock types except for very soft (no wear on the pin) and very hard rocks (no groove on the specimen). He also noted that in rocks with bands or veins and in coarse-grained rocks the position of scratches is of great importance, since it could represent hardness of a certain mineral instead of the rock. In addition, if the specimen is anisotropic, banded or markedly bedded, tests should be performed at different orientations to get a better representation of constituent minerals. Al-Ameen and Waller (1994) also confirmed West's findings and recommend higher degree of care in selection of the location and direction of the tests.

3 Experimental Studies

As can be seen, there are several sources of error associated with performing the Cerchar test which have to be addressed to make the test repeatable and reliable. The Cerchar test has become more or less the standard test for rock abrasivity evaluation in various applications such as TBM, roadheaders, and other rock excavations. Variation

in test results could cause differences in the estimated cost of projects.

In general, the discrepancies in test results can be classified into two major categories, namely, the issues related to the differences in performing the test and problems associated with intrinsic shortcomings of the test such as scale of the test (short distance), as well as the sources of errors related to final measurement of the wear flat. The issues related to the inherent characteristic of the Cerchar test need to be studied in more detail to modify the test or develop a new test. This involves development of a test that is simple, repeatable, less operator sensitive, and possibly suitable for on-site application, meaning that the equipment should be portable. In this study, the authors tried to develop a new test as an alternative to the Cerchar test with the aim of eliminating its shortcomings. Preliminary results of this new test are presented at the end of this paper.

To evaluate the issue of repeatability, a series of tests were performed on seven selected rock specimens. The same specimens were shipped to other labs for testing. The specimens were selected to cover a wide range from non-abrasive to very abrasive rocks. Cerchar tests were performed on all the seven rock types both on sawn and rough surfaces using two set of styli with different Rockwell hardness (HRC 41/43 and HRC 54/56). The equipment used was similar to the one used by West which is currently manufactured by ErgoTech Company. A set of physical indices and geomechanical tests along with mineral content evaluation were performed. Geomechanical tests included Uniaxial Compressive Strength (UCS), Brazilian Tensile Strength (BTS), Ultrasonic wave velocity, Young's modulus, and Poisson's ratio. Cerchar tests were performed using five styli for each test. Results of the performed tests are summarized in Table 1. The effect of different parameters on the test results are discussed in the following sections of the paper.

3.1 Influence of Pin hardness

Michalakopoulos et al. (2006) tested 68 specimens from six rock types with steel styli of both HRC 55 and 40. No specification of the surface conditions were given; however, the results did indicate the existence of a linear relationship (Eq. 1) between the CAI for pins of different hardness as follows.

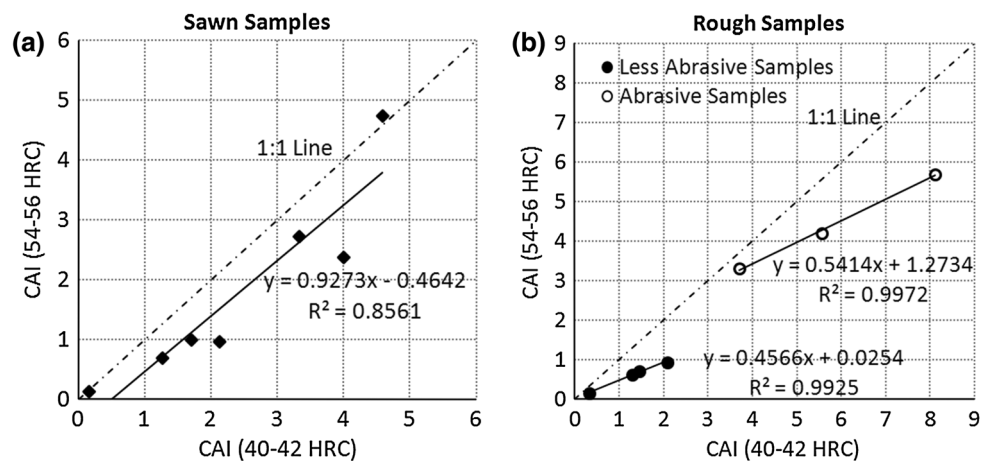
$$CAI_{55} = 0.587356CAI_{40} + 0.110914 \quad (1)$$

where CAI_{55} is the Cerchar abrasivity index using HRC 55 pins while CAI_{40} uses HRC 40 pins.

In this study, the influence of pin hardness on the measured values of wear flat or Cerchar index was examined by performing a series of tests using two different pin hardnesses on the selected set of seven rock specimens.

Table 1 Results of Cerchar and performed index tests on seven selected rock specimens

	Limestone	Slate	Calcite	Marble	Sandstone	Granite	Quartzite
Cerchar 41/43 HRC-Sawn	0.2	1.3	1.7	2.1	4.0	4.6	3.3
Cerchar 41/43 HRC-Rough	0.3	1.3	1.5	2.1	3.7	5.6	8.1
Cerchar 5 4/5 6 HRC-Sawn	0.1	0.7	1.0	1.0	2.4	4.7	2.7
Cerchar 5 4/5 6 HRC-Rough	0.2	0.6	0.7	1.0	3.3	4.2	5.7
Dry density	2.04	2.75	2.71	2.68	2.62	2.64	2.63
Porosity (%)	18.8	0.9	0.2	0.3	2.5	0.6	0.5
E (GPa)	17	75	41	67	21	49	70
Poisson's ratio (ν)	0.19	0.17	0.22	0.25	0.25	0.18	0.09
UCS (MPa)	36	121	68	133	127	184	291
BTS (MPa)	3.4	–	5.1	11.1	8.6	7.8	17.9
P -wave velocity (m/s)	4,174	7,504	4,249	4,989	3,528	5,129	6,856
S -wave velocity (m/s)	2,139	3,475	2,804	3,318	2,586	2,691	3,753
Equivalent quartz content (EQC %)	4	2	4	4	54	58	100

Fig. 6 Plot of Cerchar test results for HRC 54/56 vs. HRC40/42 pins with various specimen surface conditions (**a** sawn surface, **b** rough surface)

The summary of the results is shown in Fig. 6. In this figure, the dashed line shows a 1 to 1 slope. As anticipated, CAI with pins HRC 41/43 is higher than CAI with pins HRC 54/56 for both sawn and rough specimens.

A linear relationship can be observed in the graphs, especially for the tests performed on the rough specimens (Fig. 6b). It appears that CAI values for rough specimens can be categorized into two different groups: one for less abrasive rocks, and the other for abrasive rocks as displayed in Fig. 6b (perhaps the breaking point between the abrasive and non-abrasive could be CAI of 3). The slopes of both lines in Fig. 6b are similar to the slope of Eq. 1 as reported by Michalakopoulos et al. (2006).

It also appears that the slope of more abrasive specimens with rough surface is the same as 1:1 line, meaning that the slope of two studies does show a reasonable match. The 1:1 line is added to the graphs in Fig. 6a and b for ease of comparing measured values. The observed behavior is further confirmed when one considers the fact in Michalakopoulos' study, among the 66 tests, only six of them had

the CAI₅₅ greater than 3 with the maximum value of 3.76. This explains the reason for larger differences between the values of CAI₅₅ predicted by Eq. 1 and the results in the current study. The impact of relative hardness on the wear, which has been documented in tribology and wear calculations as explained by Natsis et al. (2008) can be observed in Fig. 6b as well.

3.2 Influence of Surface Condition

Figure 6 shows the influence of surface condition on the CAI results. As displayed in this figure, lower CAI values (non-abrasive rocks) on sawn and rough surfaces are more or less the same, which coincide with Al-Ameen and Waller (1994) conclusion. However, in specimens with higher CAI values, the results of testing on rough surfaces are higher than on sawn surfaces, which confirm the conclusions of Plinninger et al. (2004), and Rostami et al. (2005).

This behavior can be due to the fact that the strength of less abrasive rocks is usually low. This leads to the

Table 2 Cerchar, UCS, and equivalent quartz content values of eight rock types

Rock type	Cerchar-54 HRC-Sawn	Cerchar-54 HRC-Rough	UCS (MPa)	Equivalent quartz content (EQC %)
Basalt	2.37	2.49	83	32
Quartzite	2.34	3.63	165	100
Tonalite	3.23	3.25	112	48
Limestone	1.15	1.02	77	2
Gneiss	2.57	2.18	62	71
Granite/pegmatite	2.71	2.99	100	56
Amphibolite/hornblende Schist	3.56	3.79	137	40
Aplite/fine-grained Granite	3.12	3.29	140	84

penetration of the pin into the rock. Therefore, in such conditions, the roughness of the surface is not as important. However, in stronger rocks, the rock does not let the pin penetrate into the surface of the specimen, effectively forcing the pin to slide on the surface. Therefore, in harder and stronger rock specimens, pins usually slide on the surface of the sawn specimens. In contrast, in rough specimens, the pin needs to follow an irregular shaped path that leads to higher CAI values. This observation is consistent with measured amount of pin penetration into the surface of the specimens in the study by Al-Ameen and Waller (1994) and recently by Hamzaban et al. (2013).

3.3 Relation of CAI and Petrographical and Geomechanical Properties

Equivalent quartz content (EQC) of the specimens was calculated based on mineral content evaluation and their respective Rosiwal hardness using the method mentioned by Thuro (1997). CAI values were related to various rock properties and the best correlations were found between the UCS and EQC. To expand the available dataset for determination of the relationship between CAI and rock petrographic and mechanical properties, the measured rock properties for the eight additional rock types (shown in Table 2) that were available to the authors from previous studies were added to the seven selected specimens in the current study. In addition, data published by Lee et al. (2013) were received from the research team at Seoul National University and were added to the dataset for statistical analysis. This data set includes 19 different rock types and the result of their analysis as well as the actual measured rock properties can be found in Lee et al. (2013) and is not repeated here.

For statistical analysis, the Minitab software was used to obtain the best fit equations (Eqs. 2, 3) between the dependent parameter, in this case the measured CAI, and the independent variables. These equations represent the dataset from 15 specimens used in this study. Strong correlations were found between measured rock physical properties and the Cerchar Index. In each set, the equations using power functions show a good correlation and can offer realistic values for cases where very low UCS or EQC (near zero) are encountered. Equation 4 shows the result of best fit analysis for the dataset with the additional measured rock properties on 19 specimens for a total of 34 rock types. While the correlation coefficient is slightly lower, it could be considered as a better representative of the natural scatter in dealing with rock. Figure 7 shows the measured versus predicted values of CAI from UCS and EQC based on Eq. 4.

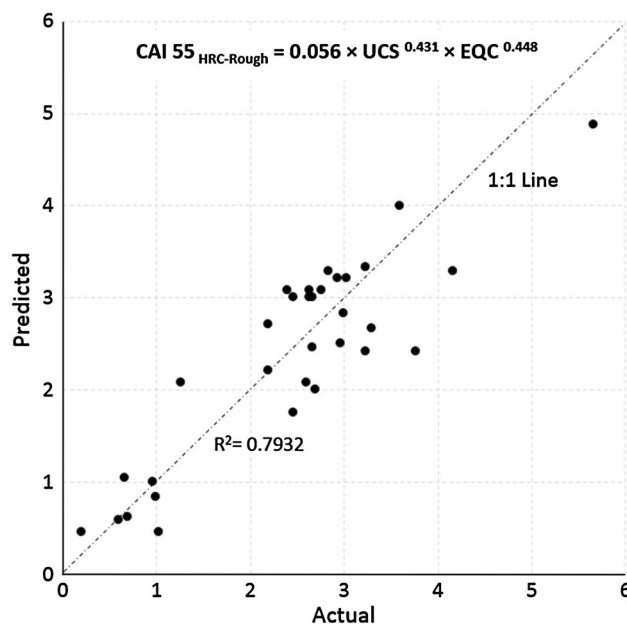


Fig. 7 Comparison of the measured vs. predicted CAI from UCS and EQC based on Eq. 4

Table 3 CAI test results for different pin speeds

Pin hardness	54–56 HRC				41–43 HRC			
	5	10	30	60	5	10	30	60
Sawn								
Limestone	0.1	0.1	0.2	0.2	0.3	0.2	0.3	0.9
Sandstone	2.9	2.4	2.7	2.5	4.2	4.0	4.1	4.0
Quartzite	3.1	2.7	2.8	2.6	3.3	3.3	3.5	3.3
Rough								
Limestone	0.2	0.2	0.1	0.1	0.3	0.3	0.4	0.4
Sandstone	2.7	3.3	2.5	2.7	3.7	3.7	3.2	3.3
Quartzite	5.2	5.7	5.1	5.2	6.8	8.1	8.6	7.5

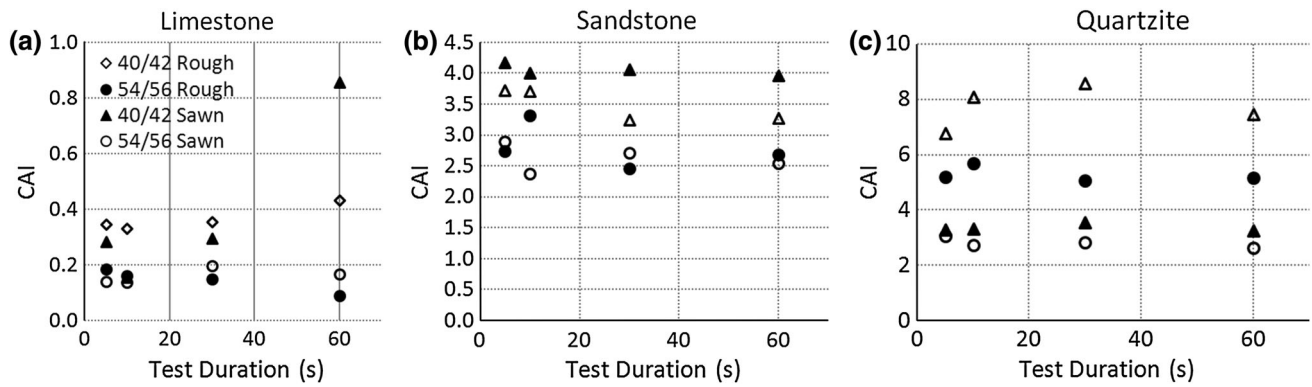


Fig. 8 CAI results with different pin speed a limestone, b sandstone, c quartzite

$$CAI_{42HRC-Rough} = 0.005917 \times UCS^{1.14} \times EQC^{0.208} \quad (2)$$

$R^2 = 94.6\%$

$$CAI_{54HRC-Rough} = 0.0151 \times UCS^{0.788} \times EQC^{0.377} \quad (3)$$

$R^2 = 89.9\%$

$$CAI_{55HRC-Rough} = 0.056 \times UCS^{0.431} \times EQC^{0.448} \quad (4)$$

$R^2 = 79.6\%$

3.4 Influences of Pin Speed

Variability of the speed of the pin on the rock surface has not been examined thoroughly by previous researchers, and a direct set of measurements of CAI at various pin speeds cannot be found in the literature. Thus, it was decided to perform a set of tests on three different rock types ranging from non-abrasive to very abrasive to evaluate the influence of testing speed. The rock types included limestone, sandstone, and quartzite. Specimens were tested for the pin moving along the 10-mm stroke in 5, 10, 30, and 60 s. Results of the testing are summarized in Table 3.

Correlation between CAI and test duration is shown in Fig. 8. The figure shows no meaningful trend and it can be concluded that the speed of the tests does not affect the results significantly. Meanwhile for Cerchar tests using the screw feeder for movement of the pin (as in the Ergotech unit) it seems like 10–20 s for the test duration (0.5–1 mm/sec) could be a reasonable rate, since it is more convenient for the operator. This produces more consistent testing results among different operators.

3.5 Influence of Varying Applied Load

A brief review of the available literature showed that there is no documented research on the influence of applied load on CAI value. As a first step toward developing a new test, it was deemed necessary to evaluate the effect of varying stresses and forces at the pin tip to see if there is a threshold stress level that accelerates the material deformation process at the tip. In addition, the testing shows the sensitivity of the CAI results to variation in dead load, given geometry and test conditions.

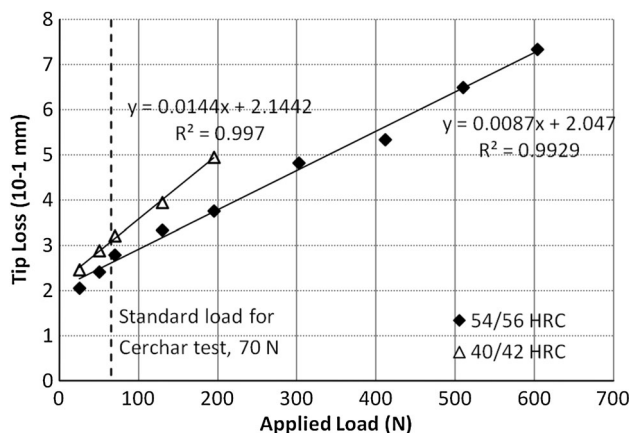


Fig. 9 Correlation between CAI and applied force on the stylus

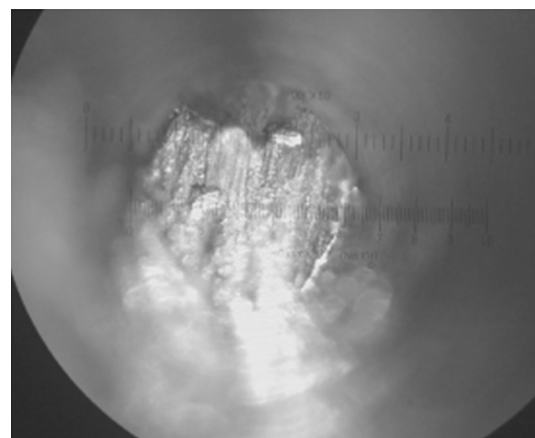


Fig. 10 Typical view of wear surface from the top (after Rostami et al. 2005)

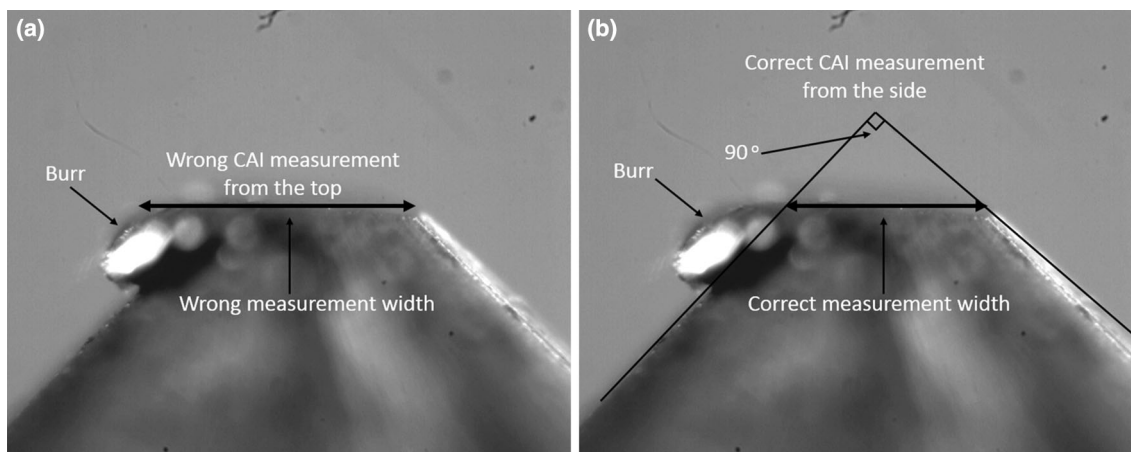


Fig. 11 View of pin tip wear surface measured from **a** the top view and **b** the side view

Therefore, a set of tests on a saw-cut quartzite were performed. Selection of the quartzite for this series of testing was due to the higher strength of the specimens, which did not allow pin penetration and creation of a groove on the rock surface and therefore, a better estimation of the contact surface and contact stress was possible. These tests were performed using two different steel hardnesses and varying applied loads. Results of these tests are illustrated in Fig. 9. As displayed in this figure, a linear relationship between the applied load and tip loss is observed. This trend occurred using steel hardnesses of 43 and 55 HRC. It can be concluded that, for a new abrasion test, the applied load is not of great importance and any load can be used; as long as the concept of the abrasivity test is the same i.e., running a hardened pin or a blade on rock surface. Another interesting observation was that the tip loss was linearly proportional to the load, while the area of contact changes by a quadratic function (D^2), meaning that the contact stresses are lower at the end of the test at higher load levels. The reason for this behavior should be investigated in future studies since it defies the logic of wear being somewhat dependent on the level of applied stresses on the steel pin, and more broadly, the rock cutting tools.

3.6 Influence of Measuring Apparatus and Procedure

Measuring the wear surface at the tip of the pin, while it is seemingly simple, poses its own challenges to produce repeatable results in CAI testing. In practice, this step of the test has the highest operator sensitivity and impact on the measured results. On fresh rough surface testing, especially in harder rock types, the wear flat can often have a non-uniform shape and splinters or burrs of steel can stretch beyond the wear flat (as shown in Fig. 11a, b). This can affect measurements by making it difficult to determine the true diameter of wear flat by top view measurements (Fig. 11a). West (1989) did also mention that a burr is occasionally

formed on the downstream side of the wear surface during testing. He suggested that the burr should be gently removed by a soft material or the extended surface must be disregarded when measuring the wear surface. However, the authors of this study found it very difficult to remove the burr. Distinguishing extended surface from top view is difficult and often time the shape of the wear flat could be misleading. Typical views of the wear surface from top and side are presented in Figs. 10, 11a and b, respectively.

Rostami et al. (2005) mentioned that the difficulties associated with viewing from the top could be considerably reduced by use of a new measuring technique, developed at NTNU/SINTEF in Norway. This system involves analyzing digital microscope photos of the wear surface taken from the side of the pins. In this system, the correct angle of the tip is determined before the actual measurement is performed. This provides correct determination of the start and end points of the wear surface. Figure 11b shows the side view of the pin tip under the microscope used for measuring the diameter of the wear surface, while Fig. 11a shows the wrong measurement from the top.

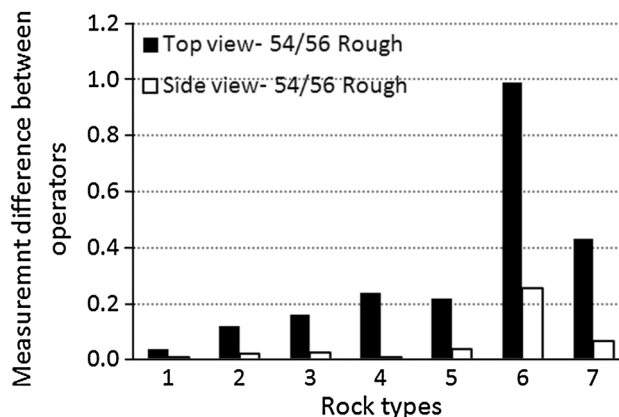


Fig. 12 Variation of CAI measurements between operators

Table 4 Results of Cerchar tests on the selected seven rock specimens performed by different laboratories

Laboratory	Lab 1		Lab 2		Lab 3		Lab 4		SINTEF		Lab 5		PSU					
	Pin hardness (HRC)	54-56	Sawn	Rough	54-56	Sawn	Rough	54-56	Sawn	Rough	41-43	Sawn	Rough	41-43	Sawn	Rough		
1	Limestone	0.5	0.4	0.6	0.5	0.3	0.8	0.4	0.9	0.3	0.3	1.4	0.4	0.3	0.2	0.3	0.1	0.2
2	Slate	1.1	1.1	1.8	1.6	1.9	1.4	1.8	2.3	1.4	1.6	2.4	1.2	0.9	1.3	1.3	0.7	0.6
3	Calcite	0.8	0.9	2.6	3.0	2.3	1.1	0.7	1.2	2.1	1.7	3.1	1.1	0.7	1.7	1.5	1.0	0.7
4	Marble	1.0	1.0	3.1	2.8	2.6	1.6	1.7	2.2	2.3	2.3	3.1	1.3	1.6	2.1	2.1	1.0	1.0
5	Sandstone	3.7	4.2	4.3	4.1	4.5	2.7	3.2	3.6	3.8	3.8	5.7	3.8	4.1	4.0	3.7	2.4	3.3
6	Granite	4.2	4.4	4.9	4.8	4.3	4.6	4.6	5.0	4.4	5.5	5.7	4.7	4.5	4.6	5.6	4.7	4.2
7	Quartzite	3.6	5.8	4.7	5.5	4	2.6	4.3	4.7	3	6.4	3.4	3.0	7.2	3.3	7.1	2.7	5.7

Participating labs in alphabetic order: Advanced Terra Testing, Inc., Colorado School of Mines, SINTEF, SubTerra, Inc., TerraSense, LLC., University of Texas at Austin (does not correspond to assigned lab # to assure anonymity)

To evaluate the precision of this method, a series of tests were performed on the set of seven rock types as discussed before (Table 1). After performing the test on each rock type, the wear surface was measured by two different operators using a microscope from the top and also using a digital microscope from the side. Tests were performed both on sawn and rough surfaces with HRC 54/56 pins. Test speed was 1 mm/sec or 10 s per pin scratch. Results of these tests are summarized in Fig. 12. As illustrated in this figure, variation decreased significantly when measuring the diameter of the wear surface from the side. This proves that measuring the wear flat from the side view image can reduce the operator effect on the test.

4 Comparing Cerchar Results from Various Laboratories

Several rock mechanic laboratories in the US and around the world were invited to participate in this study by conducting Cerchar tests on the aforementioned seven rock specimens. Results from seven laboratories are summarized in Table 4. The data generated in this collaborative effort are used to further study the influence of different parameters on CAI. The effects of various pin hardnesses are shown in Fig. 13.

By comparing the graphs in Figs. 13 and 5, similar trend can be seen. However, the slope of the trend lines for rough specimens is different. This shows that the general finding of the study, which shows a linear relationship between CAI values for pins with different hardness is true. In addition, two different trends for abrasive and non-abrasive rocks can be seen in the data from different labs. However, defining a new formula requires more tests. Figure 14 shows the influence of the specimen’s surface condition on CAI value using the results from different laboratories. Again, similar trend can be identified by comparing the graphs in Figs. 5 and 14.

Figure 15a–d illustrates the results of tests performed by the collaborating laboratories versus the measured CAI values by Penn State University using the side view technique. As can be seen, there are some variations between the results obtained by various labs using identical specimens and test settings. As discussed before, this was anticipated because of the inherent shortcomings of the test and also variation in performing the test among different laboratories. One interesting finding of the results from HRC 41/43 pins is that the results from SINTEF and PSU are very close. This is an important observation, since both laboratories use a similar method for measuring the pins wear surface. As discussed earlier, using this method can decrease the variation between readings significantly and improves repeatability of the measurements.

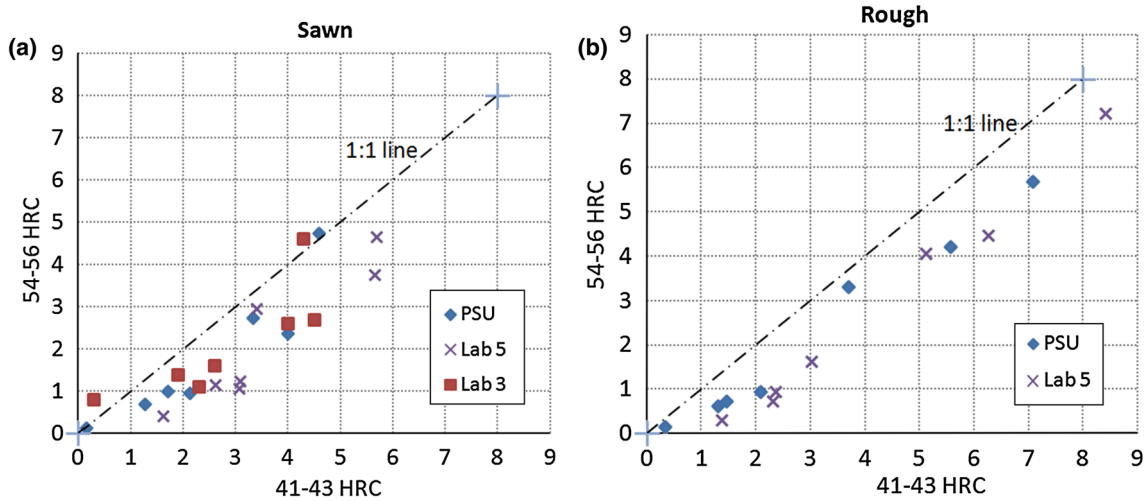


Fig. 13 Influence of pin hardness on CAI value using results from various labs **a** sawn surface, **b** rough surface

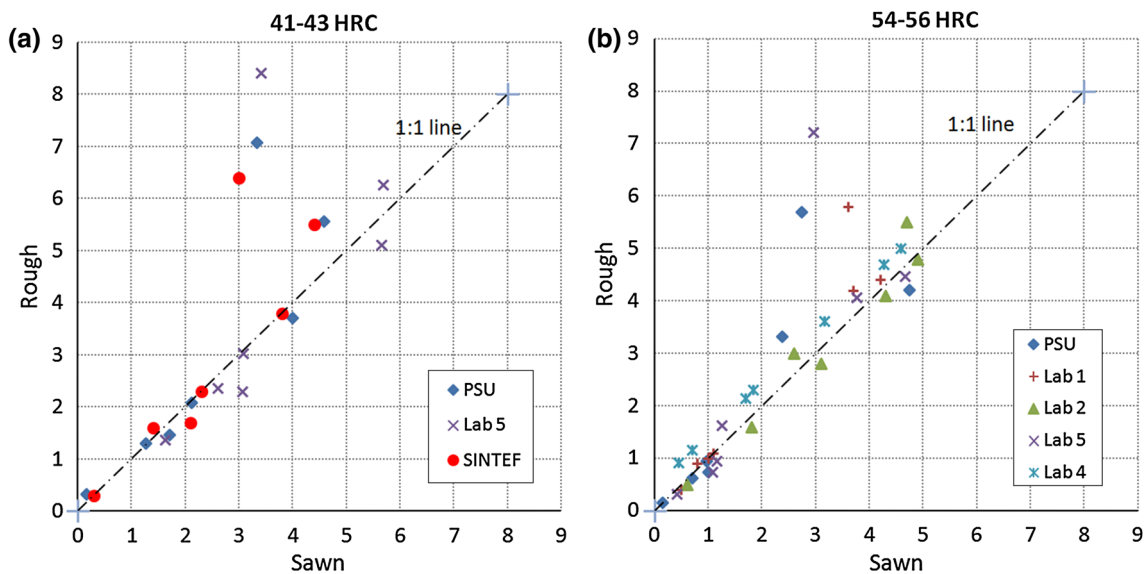


Fig. 14 Influence of surface condition on CAI value using results from various labs **a** HRC 41/43 **b** HRC 54/56

5 Study of Alternative Testing Configuration for Measurement of Rock Abrasion

To examine the possibility of developing a new rock abrasivity test to address the issues related to the Cerchar test on repeatability and operator sensitivity, a series of tests were conducted. For this purpose, the test parameters and setting used in Cerchar index testing were analyzed to identify the areas of potential improvement and a new device was designed for some initial testing and verification. One of the major drawbacks of the CAI is small-scale testing of the rock surface. Another significant shortcoming of the test is that the applied stress on the pin is not constant throughout the test. This is due to the geometry of the

tool which is a sharp cone with theoretical zero diameter at the beginning of the test. As the test progresses, the tip wears and the magnitude of the stress at the pin tip decreases. Therefore, depending to the abrasivity of the rock and hence the size of the flat area, the actual contact stress at the pin tip differs between various specimens of the same rock type.

A new prototype equipment was designed, fabricated, and subsequently used for preliminary testing of the new abrasion index measurement concept. The equipment used for the preliminary test is a small machine shop lathe that can hold the core specimen in the chuck and rotate it while a stylus is pressed against the rock surface. The device simply consists of a handle mounted on a frame, which can

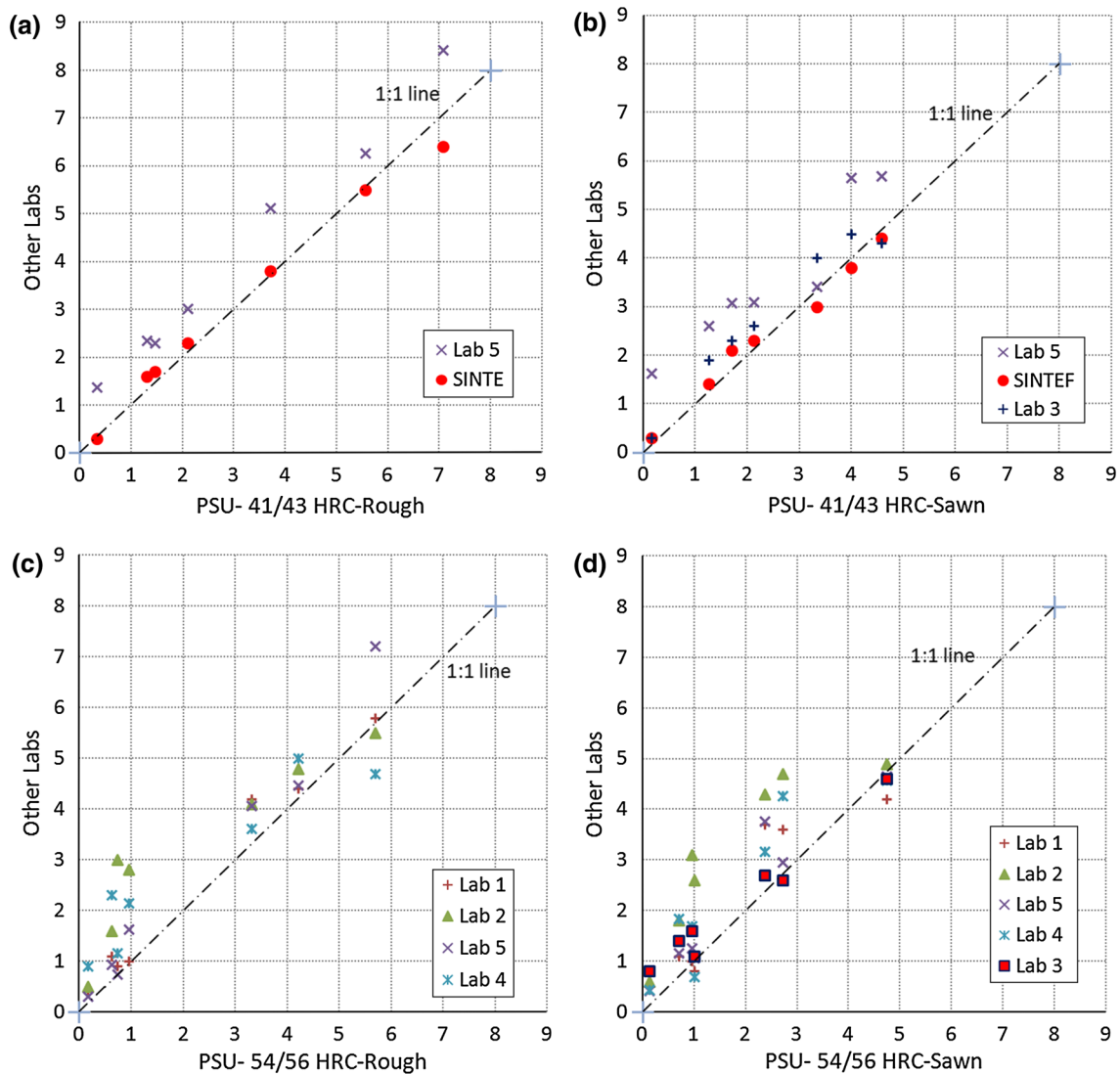


Fig. 15 Comparison the CAI results of different laboratories **a** HRC 41/43, rough surface **b** HRC 41/43, sawn surface **c** HRC 54/56, rough surface **d** HRC 54/56, sawn surface

transfer a vertical applied (dead) load into the horizontal load applied on a pin which is guided through a cylinder and pressed against the rock surface on a specimen that is held and rotated on chuck. Different applied loads can be obtained by applying different weights or just by changing the location of the dead weight on the upper surface of the swinging arm. Figure 16 shows the design concept and the preliminary version of the new equipment. The specimen is held by the chuck of a lathe machine and can be turned at different revolution speeds. Therefore, by changing the duration of the test, rotational speed of the specimen, and also distance from center of the core different scratch lengths can be obtained. For the preliminary testing, it was decided to use the same HRC 54/56 pins, which are used in Cerchar testing.

A set of preliminary tests were performed on the seven rock types, which were discussed earlier. All tests were performed on sawn surfaces. The distance between pin tip and core center was 1.5 cm (~ 0.6 in.) for all tests. The rotational speed was set at 52 rev/min, and the test duration was selected to be 5 min. Scratch length can be calculated as 2.5 m (~ 100 in.) for the given test geometry. No weight was put on the handle, meaning that the weight of the handle itself was used as the applied load on the pin. The applied load on the pin tip with no additional weight was measured to be 2.8 kg. Results of the initial tests are presented in Table 5.

Figure 17 shows the relation between the results of new test with CAI for different rock types. As can be seen in this figure, no meaningful correlation can be seen where

Fig. 16 a Schematic view of the new equipment and **b** the preliminary version of new equipment for rock abrasion testing

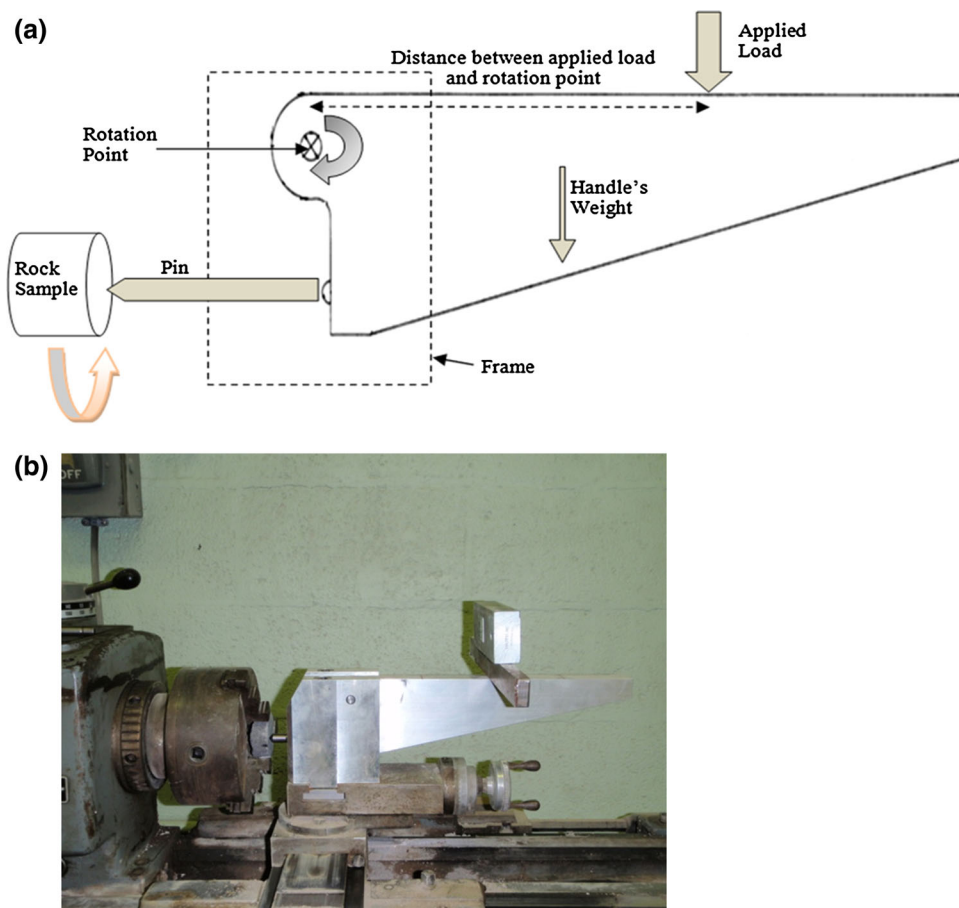


Table 5 Results of the new equipment along with respected CAI value for seven rock types

	Average tip loss (10 ⁻¹ mm)	CAI 54–56 rough	CAI 54–56 sawn
Limestone	0.8	0.2	0.1
Slate	7.9	0.6	0.7
Calcite	2.2	0.7	1.0
Marble	2.2	1.0	1.0
Sandstone	16.5	3.3	2.4
Granite	8.2	4.2	4.7
Quartzite	8.9	5.7	2.7

the tip loss of the pin is compared to the measured Cerchar index.

The lack of correlation could be attributed to the fact that in the Cerchar test, the length of the test is limited and therefore the only part which wears out during the tests is the tip of the pin. But in the new test, the pin tends to penetrate into the rock surface, especially for softer rocks. In all soft rocks, a deep groove was produced in the rock surface within the first few seconds of the test. This led to the contact of the body of the pin with the rock in a long distance of the test which is similar to the condition of tools during excavation.

As the pin cannot rotate during the test, wear occurs on two opposite sides of the tip. This shows that the method of evaluating wear by measuring the tip loss with a microscope cannot be directly applied here. This is due to the higher magnitude of wear on the tip and also the shape of the wear surfaces which is not flat. Therefore, other methods like weight loss should be considered for measuring the rock abrasivity in the future tests. In preliminary tests, the side view of the pin was used for measurement of the wear surface but at lower magnification.

Another set of tests was performed on quartzite to study the influence of test duration/scratch length and different load levels. For all tests, the distance between the tip and core center was 1.5 cm (~0.6 in.) as before. In addition, the rotational speed was kept constant at 52 rev/min. Tests were performed for six different durations (0.5, 1, 2, 5, 10, and 30 min) and were carried out at four different loading levels: without any additional weight except for the weight of the handle, 2.3 kg weight at the distance of 7.6 cm (3 in.), 15.2 cm (6 in.), and 22.9 cm (9 in.) from pivot point of the arm. The selected weights used in testing were nominal, meaning that no attempt was made to get an exact weight target, rather a range of various applied loads were used in the testing. Three pins were used for each test, and

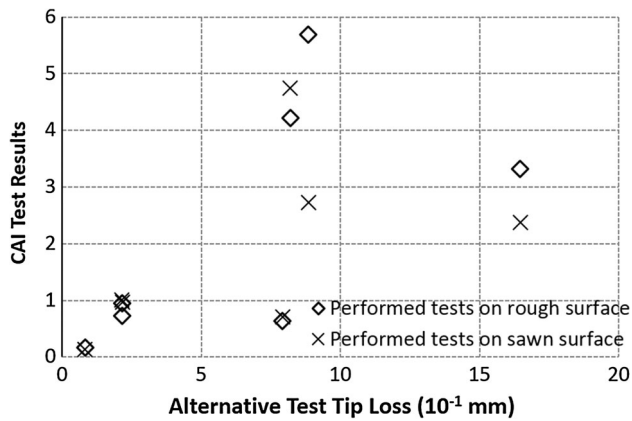


Fig. 17 Comparison between the results of testing using the alternative testing system and CAI on seven rock types

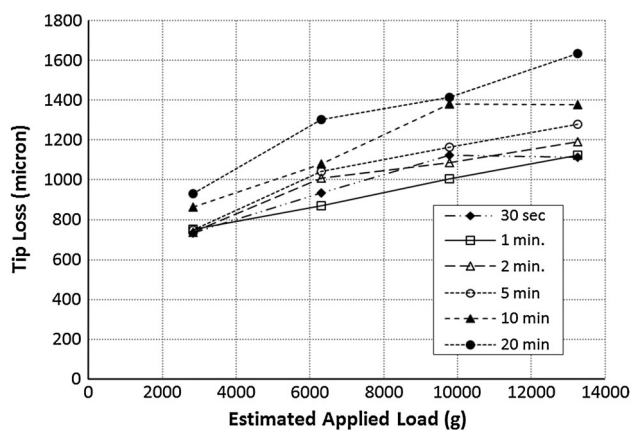


Fig. 18 Relation between applied load, scratch length, and tip loss in new equipment

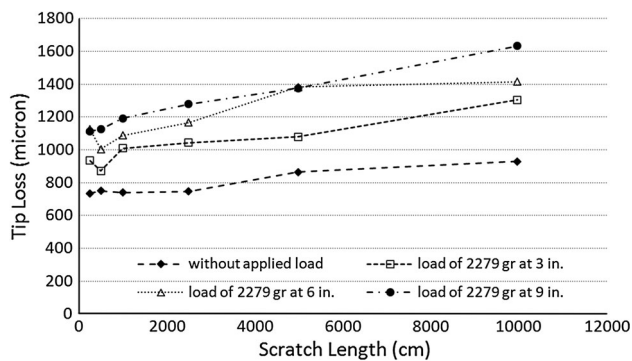


Fig. 19 Correlation between scratch length or test duration and the tip loss in new equipment

the average value of the measured wear surface was calculated.

The estimated applied load correlates well with tip loss. The result of this set of tests is shown in Fig. 18. The plot of measured tip losses shows a linear relationship between

the applied load and the tip loss (similar to the trend observed in the Cerchar test). This suggests that the magnitude of load is not of great importance in both tests and any load can be used as the standard for future tests. In other words, any nominal level of load can be selected and used as standard, and variation of the load within the ranges of testing does not change the wear behavior of the stylus in a step function or in a non-linear manner that could cause change in results as related to level of loading used for standard testing. Another conclusion is that if for any reason a different load level is used in a set of tests, it can be adjusted to the correct value of applied load to obtain standard reading and measurement.

Figure 19 shows the relation between scratch length and the tip loss. As can be seen, at the beginning of the test, a significant wear occurs and during the testing, the size of the wear surface grows at lower pace.

This coincides with the results of the Cerchar tests and suggests the use of other tip shapes rather than a cone-shaped pin for development of the future tests could be considered. The test shows that with increased duration of the test the wear surface increases in size, meaning that it could provide a value for surface hardness and abrasivity of the rock specimen over extended test section. This indicates that a nominal scratch length can be selected and used for comparative index testing, perhaps in conjunction with a cylindrical pin shape and measurement of weight loss of the pin during the testing. Once this test is fully developed and results verified, it could be modified to a smaller size that is portable and can be used in field application if needed. In summary, the results of initial testing show that much additional work is needed to develop a reliable, accurate and repeatable rock abrasion testing that could be applied to a wide range of rock specimens.

6 Conclusion

There are some discrepancies in the Cerchar test results obtained from various laboratories that are due to the type of equipment used, condition of the rock specimens, operator skills and procedures followed in testing and final measurement of the wear surface. In this study, potential solutions to achieve more uniform testing and more consistent/repeatable test results were offered. The study shows that some test parameters such as speed of testing and length of the scratch in soft to medium rock specimens do not have a significant impact on the end results.

The study included measurements of petrographical and geomechanical properties of the specimens to evaluate the relationship between measured CAI and some other rock

properties for cross checking the end results of Cerchar tests. Comparison of the CAI values and the physical properties of the rock indicated that CAI measured on rough specimens yields more consistent results and good correlation with UCS and EQC values. It was also concluded that there is a linear relationship between CAI values for different pin hardnesses, especially for rough specimens. Two different trends can be seen for non-abrasive and abrasive rocks, which can be related to the relative hardness of the tool versus the rock. In addition, test results show that the surface condition is not of great importance in softer rocks while it has a significant influence on the stronger rocks. In general, it is recommended to use the rough surfaces in the tests as leads to more repeatable and consistent results. This is in counterintuitive when thinking about a wear test on a flat sawn surface.

In addition, the study showed that variation of pin speed does not have any systematic and meaningful impact on the test results. Testing various levels of applied load on the pins illustrated that while the results of measured wear surface will increase linearly with applied load, it does not seem to offer better or more consistent results at higher load levels. To address the issue of operator sensitivity on the measurement of wear surface, this study confirmed that variation of test results are small if the diameter of the wear surface is measured from the side by a microscope.

Results of Cerchar tests on the same specimens in different laboratories show that the differences between the reported results could sometimes be significant, depending on the testing apparatus, procedures, and measurement style.

A new rock abrasion testing concept was developed, and initial tests were performed to address some of the drawbacks of the Cerchar test. The initial testing included different scratch lengths and various loading levels on the pin. The preliminary results indicate that after a certain distance, increasing the length of the scratch does not have a significant effect on the wear or tip loss. In addition, the variation of the applied load showed a linear trend with wear surface, similar to the changing of the dead weight on the Cerchar test. Additional testing is underway to evaluate the other testing parameters on the proposed device to evaluate the operator sensitivity and repeatability of the test.

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