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Effects of mechanical and mineralogical properties on CERCHAR abrasivity index and specific energy of some Thai rocks

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Abstract

The objective of this study is to determine the correlations between CERCHAR abrasivity index (*CAI*) and mechanical and mineralogical properties of twenty rock types encountered in mining and construction industry in Thailand. These rocks represent soft to medium strong rocks on which their *CAI* properties have rarely been investigated elsewhere. Results indicate that fair correlation is obtained between *CAI* and rock strength. *CAI*'s increase linearly with friction angle, they however show no correlation with the cohesion. Minerals composing each rock type obtained from XRD analysis are used with their corresponding Moh's scale hardness to determine volumetric hardness (H_V) of the specimens. H_V's can correlate with rock abrasivity better than the widely used equivalent quartz contents. Both parameters give better correlations with *CAI* when clastic and crystalline rocks are analyzed separately. Scratching groove volume reduces exponentially with increasing rock abrasiveness. CERCHAR specific energy (*CSE*) correlates well with all rock groups, providing that only hardness of soft minerals in clastic rock group is used in the regression. *CSE* also increases with *CAI*'s, suggesting that rocks with high abrasivity require higher energy to cut, and yield lower excavated volume than those with lower abrasivity. The research findings can be used to predict the wear of excavation tools in soft to medium strong rocks using the correlations between *CAI* test results and their mechanical and mineralogical properties.

Keywords: Abrasiveness, Rock strength, Friction angle, Rock hardness, Mohs scale

1. Introduction

Rock abrasiveness is a primary factor determining the equipment life and directly affects operation costs in terms of machine performance, worn-out parts and delays in mining and construction industry. One of the methods for determining rock abrasiveness is CERCHAR abrasivity index (*CAI*) test [1]. The method has become popular due to its simplicity, speed and low cost [2, 3]. It has been widely used in the French and British coal mining industry. In 2010, American Society for Testing and Materials (ASTM D7625-10) has standardized the CERCHAR testing method [4] and, later withdrawn in 2019. International Society for Rock Mechanics (ISRM) has also published test procedure, device, and calculation for *CAI* test as proposed by Alber et al. [5]. The ISRM suggested method has made corrections on the measurement and calculation procedure. In 2022 ASTM (D7625-22) [6] has published an updated version for CERCHAR abrasiveness index test method. It is similar to the previous one in 2010 accept that the multiplied factor for converting *CAI* from smooth surfaces to rough surfaces has been changed to be identical to that of ISRM for low abrasiveness rock ($CAI < 4$). CERCHAR test uses a steel stylus with a 90 degrees conical tip, which is pinned perpendicular on the rock surface under a constant force of 70 N. The length of stylus scratching on the rock surface is 10 mm. The wear flat width of stylus tip is measured to the nearest 0.1 mm. The scratching is repeated five times with five individual re-sharpened pins for each specimen to achieve an average *CAI* value. The use of stylus hardened to 55 ± 1 HRC is advised. A microscope for examining the wear flat stylus has a minimum magnification of 25 times for ISRM [5] and 30 times for ASTM [6].

Several investigators have identified factors affecting the CERCHAR test results which can be divided here into two main groups: test parameters and rock properties. Al-Ameen and Waller [7] conclude from their experimental results that 85% of the *CAI* is occurred within 2 mm of scratching length and only about 15% of the change in *CAI* occurs within the last 8 mm. This is confirmed by the results obtained by Plinninger et al. [8]. Variation of the scratching speeds (rates) from 3, 10 to 20 mm/s does not significantly affect *CAI* value [9]. Hamzaban et al. [10] however note that increasing pin speed can increase the wear of stylus tip. This is later supported by experimental results obtained by Kotsombat et al. [11] who conclude that reducing pin speed by up to 1 to 3 orders of magnitude can significantly decrease scratching force and *CAI* value, and results in a deeper groove on rock surface.

It has been found that physical and mechanical properties and mineral compositions of rock specimens significantly affect the wear of stylus tip during *CAI* testing. Plinninger et al. [8] conclude from their test results that *CAI* obtained from rough surfaces is about twice of smooth surfaces. Similar results are obtained by Aydın [12], Käsling and Thuro [13] and Yaralı and Duru [14]. *CAI* also increases as the rock porosity decreases [15-17]. *CAI* has been extensively used to correlate with uniaxial compressive strength of rocks [16, 18-20]. Positive linear relations have commonly been found with low to fair coefficients of correlation. Deliormanlı [21] states

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that uniaxial compressive strength plays an important role for abrasiveness of the rock. This agrees with a conclusion drawn by Al-Ameen and Waller [7] that the abrasiveness is largely influenced by the rock strength (s_c).

Extensive studies have been carried out to correlate *CAI* with mineral compositions of rocks [19, 22, 23]. Rocks containing hard and highly abrasive minerals (such as quartz) tend to induce higher wear of stylus tip, as compared to those containing softer and lower abrasive minerals. Grain size and shape of minerals also play a significant role in the *CAI* values. High wear is usually obtained from rocks with large quartz grain sizes of more than 0.5 mm. For quartz grain size less than 0.1 mm, no significant wear of stylus tip is found [22]. Even though various aspects of research results from *CAI* testing have been compiled, most of them are from medium to very strong rocks, as they can induce high wear on excavation tools and machines. *CAI* testing on soft rocks has rarely been performed.

The objective of this study is to correlate *CAI* with the mechanical and mineralogical properties of soft to medium strong rocks. The test specimens are prepared from rocks commonly found in Thailand, in particular those encountered in mining and construction projects. A new method for determining the effect of mineral compositions on *CAI* values is present. The different responses of *CAI* to crystalline rocks and clastic rocks are identified.

2. Sample preparation

Twenty rock types have been prepared for CERCHAR and compression testing. They are categorized here into six groups, as shown in Table 1. These rocks are commonly found in the north and northeast of Thailand, where they are subjected to various excavation tools in mining and construction industry. For example, rock salt is excavated by roadheaders in Chaiyaphum province. Granite and marble in Saraburi province are cut by diamond wire saw for decorating stone production. Tunnel boring machines (TBM) are the main tool for excavating railway tunnels in the north and northeast of the country. In Nakhon Sawan province drum cutters are widely used in gypsum open pit mines.

Test specimens used in this study are drilled from rock blocks to obtain nominal diameters of 54 mm. Their end surfaces are cut flat resulting in length-to-diameter (L/D) ratios of 1, 2 and 2.5 for CERCHAR, uniaxial and triaxial compression testing. Five specimens from each rock type are prepared for each test. For sedimentary and metamorphic rock specimens, the test surfaces are prepared parallel to the bedding and foliation planes. This is to isolate the effect of transverse isotropic texture of these rocks, which represents a scope of this study. Some post-test specimens are used for determining their mineral compositions by X-ray diffraction (XRD) analysis.

Table 1 Mineral compositions of tested rocks from XRD analysis

Rock Group	Rock Type	Code	Mineral Compositions
Clastic	Phu Phan Sandstone	Kpp	86.13% Quartz, 6.27% Kaolinite, 1.65% Muscovite, 3.46% Albite, 0.60% Microcline, 1.90% Chlorite
	Sao Khua Sandstone	Ksk	71.89% Quartz, 5.29% Kaolinite, 13.77% Muscovite, 6.06% Albite, 0.23% Anorthite, 1.66% Microcline, 1.04% Oligoclase, 0.08% Chlorite
	Phra Wihan Sandstone	JKpw	83.50% Quartz, 3.94% Kaolinite, 0.66% Muscovite, 3.91% Albite, 1.03% Anorthite, 3.23% Microcline, 0.27% Calcite, 3.48% Chlorite
	Phu Kradueng Sandstone	Jpk	38.35% Quartz, 2.94% Kaolinite, 11.87% Muscovite, 22.05% Albite, 2.39% Anorthite, 4.43% Microcline, 0.24% Calcite, 9.53% Oligoclase, 8.23% Chlorite
Plutonic	Tak Granite	Cgr	27.71% Quartz, 7.97% Muscovite, 1.42% Chlorite, 18.76% Albite, 31.63% Orthoclase, 8.99% Anorthite, 3.54% Diopside
	Granodiorite	Trgr	44.82% Quartz, 6.30% Muscovite, 3.66% Chlorite, 22.59% Albite, 15.30% Orthoclase, 3.66% Anorthite, 3.69% Diopside
Carbonate	Khao Khad Marble	Pkd	93.50% Calcite, 0.46% Quartz, 4.35% Dolomite, 1.70% Chalcopyrite
	Khao Khad Limestone	Pkd	92.24% Calcite, 5.05% Dolomite, 0.22% Fluorite, 1.79% Microcline, 0.71% Actinolite
	Khao Khad Travertine	Pkd	93.48% Calcite, 0.05% Quartz, 6.02% Dolomite, 0.46% Chalcopyrite
Sulfate & chloride	Tak Fa Gypsum	Tkb	1.53% Fluorite, 98.47% Gypsum
	Tak Fa Anhydrite	Tkb	99.08% Anhydrite, 0.92% Fluorite
	Maha Sarakham Salt	KTms	95.50% Halite, 1.83% Gypsum, 0.31% Sylvite, 0.28% Anhydrite, 0.16% Dickite
Silicate	Pyrophyllite	PTRv	30.35% Dickite, 26.16% Kaolinite, 43.49% Quartz
	Dickite	PTRv	84.18% Dickite, 15.26% Kaolinite, 0.57% Quartz
	Skarn	PTRv	35.89% Dickite, 19.19% Kaolinite, 32.55% Quartz, 6.22% Nacrite, 3.30% Alunite, 2.87% Pyrite
Volcanic	Khao Kradong Basalt	Qbs	0.69% Quartz, 9.46% Muscovite, 3.89% Chlorite, 19.45% Albite, 18.68% Anorthite, 31.70% Diopsite, 16.14% Microcline
	Khao Kradong Vesicular Basalt	Qbs	0.13% Quartz, 18.14% Muscovite, 1.19% Chlorite, 43.53% Albite, 6.15% Orthoclase, 29.90% Anorthite, 0.99% Kaolinite
	Khao Yai Rhyolite	PTRv	30.99% Quartz, 26.19% Muscovite, 18.69% Chlorite, 6.21% Albite, 6.29% Orthoclase, 5.61% Anorthite, 3.66% Diopsite, 1.70% Microcline, 2.65% Kaolinite, 1.15% Hematite
	Khao Yai Andesite	PTRv	43.59% Quartz, 4.48% Muscovite, 4.28% Chlorite, 2.91% Albite, 0.80% Orthoclase, 0.46% Anorthite 43.50% Kaolinite
	Khao Yai Tuff	PTRv	7.57% Quartz, 22.49% Muscovite, 34.42% Chlorite, 16.73% Albite, 1.97% Orthoclase, 2.60% Anorthite, 5.57% Hematite, 8.66% Calcite

3. Test apparatus and methods

CERCHAR testing is performed on saw-cut surfaces of rock specimens under dry and unconfined conditions using a device based on West apparatus [24], as shown in Figure 1. The apparatus comprises vice holding rock specimen, a pin chuck or casing for stylus pin, a static load of 70 N, and a hand crank. The specimen is moved underneath the stylus. The pin has Rockwell hardness (HRC) of 55 ± 1. Test procedure follows the International Society for Rock Mechanics (ISRM) suggested method [5]. The scratching length is 10 mm. Test duration is 10 s, resulting in a constant scratching rate of 1 mm/s. This can be obtained by rotating the hand crank 10 rounds for 10 seconds, as the pitch of screw connecting between hand crank and vice holding is 1 mm. With several trials and timing practices, the desired stylus pin speed of 1 mm per second can be accurately achieved. The wear flat of stylus tip before and after scratching is measured under microscope with magnification of 50. Each stylus tip is measured around its axis in 0°, 90°, 180°, and 270° directions. The results are averaged for each pin. Five pins are used for each rock type. The CERCHAR abrasiveness index (*CAI*) values can be calculated as $CAI = d \times 10$, where d is diameter of scratch flat area of stylus tip from rough surfaces testing. The diameter d can be correlated with smooth surfaces testing (d_s) by [5]:

$$d = 1.14 \cdot d_s \tag{1}$$

It is recognized that smooth surface testing is an option for *CAI* test methods of ASTM [4, 6] and ISRM [5]. To meet the objective of determining the effects of mechanical and mineralogical properties of rocks on CAI, the effect of surface roughness is excluded here. It should be noted that surfaces roughness of rock is difficult to control, as the same rock type may yield different surface roughness values. This will add an uncontrollable variable to our test plan. Some investigators [8, 13, 25] who perform *CAI* tests on both rough and smooth rock surfaces have found that *CAI*'s obtained from rough surfaces show higher variation than those from smooth surfaces. As a result, they recommend to use smooth rock surfaces for *CAI* testing. In addition, mathematical representation of rock surface roughness requires relatively long surface profile (e.g. 10 cm for JRC [26]), while *CAI* testing uses only 10 mm. This may pose difficulty when such *CAI* is correlated with a roughness parameter, particularly when the roughness profile is not uniform along the entire length.

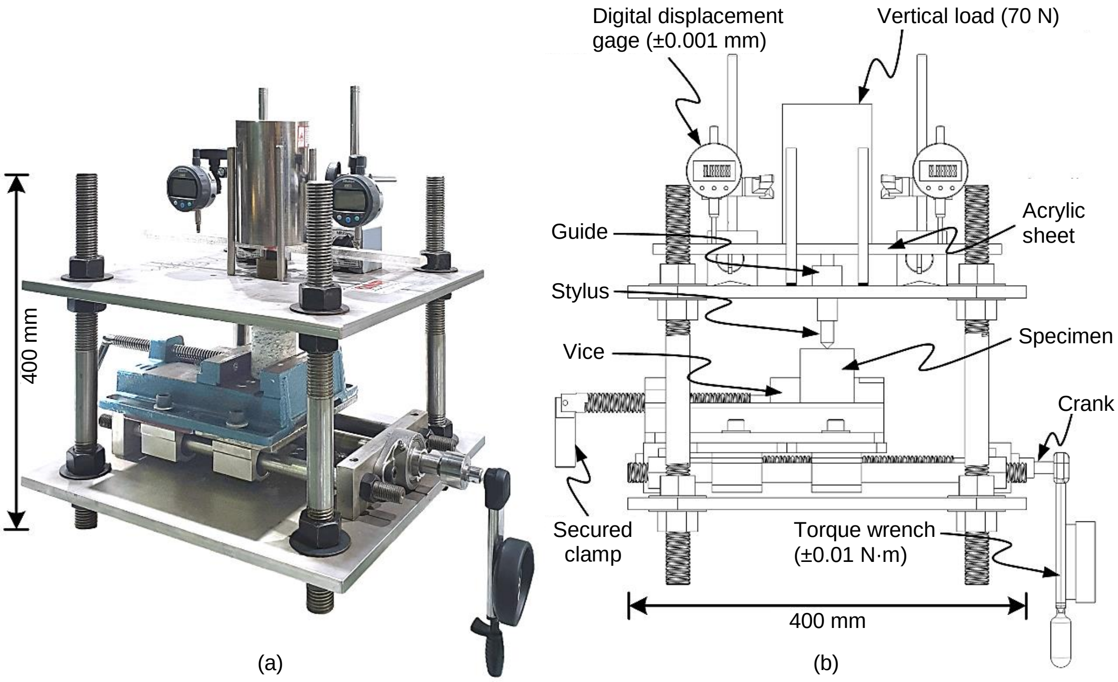

Figure 1 Device based on West CERCHAR apparatus [24] with additional torque and vertical displacement measurement (a) and schematic drawing of CERCHAR device (b).

Additional parameters are imposed beyond those suggested by the ISRM. The vertical displacement of the stylus is measured along the scratching length by digital displacement gages with a precision of 0.001 mm to obtain groove depth produced by scratching. The lateral force applied on the stylus can be calculated from torque applied on the crank. A torque meter with a precision of 0.01 N·m is used. The lateral force can be calculated by the following equation [27]:

$$F = 2 \cdot \pi \cdot T/P \tag{2}$$

where F is lateral force (N) on the stylus tip, T is torque (N·m) on the crank, and P is screw pitch (0.001 m).

Volume of scratching groove is obtained from laser-scanning profiles along the scratching length of 10 mm. The groove width and depth are measured to the nearest 0.001 mm.

For the mechanical characterization, uniaxial and triaxial compression tests are performed in accordance with the ASTM D7012-14e1 [28] standard. The axial stress is applied under a constant rate of 0.1 MPa/s until failure occurs. Axial and lateral displacements are measured by 0.01 mm precision dial gages. The confining pressures for the triaxial testing range between 0.69 and 12 MPa. Postfailure characteristics are observed and recorded. The elastic modulus and Poisson's ratio are determined from the tangent of stress-strain curves at 40-50% of the failure stress.

Some post-test CERCHAR specimens are ground to obtain powder with less than 0.25 mm particle size (passing through mesh #60). About 5 to 10 grams are analyzed using X-ray diffractometer. DIFFRAC.EVA software determines the weight percentage of the mineral compositions. Table 1 shows the results from XRD analysis.

4. Test results

Results of CERCHAR abrasivity index and mechanical testing for all rock groups are given in Table 2. Figure 2 shows examples of scratching grooves and wear of stylus tips of some rock types. High strength rocks (e.g., sandstone, granite, and pyrophyllite) tend to show higher *CAI* values than the lower strength rocks do. The Coulomb criterion can best describe the triaxial compressive strengths for all rock types. Their results are presented in terms of cohesion (*c*) and friction angle (*f*) in the table. Good correlation between Coulomb criterion and the test data are obtained ($R^2 > 0.9$).

4.1. Correlation between CAI and rock mechanical properties

CAI's are plotted as a function of uniaxial compressive strength in Figure 3(a). Similar to the approaches used elsewhere [15, 18, 29], a linear equation is used to describe their relationship:

$$CAI = 0.043 \cdot s_c \tag{3}$$

Fair correlation is obtained ($R^2 = 0.475$). Figure 3(b) compares the linear equation obtained here with those presented by other investigators, as quoted in the figure. They also obtain fair correlations ($R^2 = 0.3 - 0.5$) between the two parameters.

No correlation is found between *CAI* and cohesions of rocks (Figure 4(a)). *CAI*, however, tends to increase with friction angle, as shown in Figure 4(b), where they can be correlated by:

$$CAI = 0.076 \cdot f - 1.268 \tag{4}$$

The linear relation above shows $R^2 = 0.418$.

Table 2 CERCHAR abrasivity indexes, rock strengths, cohesions, friction angles, equivalent quartz contents, and volumetric hardness for all rocks in this study.

Rock Group	Rock Type	*CAI*	s_c (MPa)	*c* (MPa)	*f* (Degrees)	*EQC* (%)	H_V
Clastic	Phu Phan Sandstone	3.02	81.4	8.6	59	88.31	6.52
	Sao Khua Sandstone	1.85	53.1	9.7	47	76.10	6.03
	Phra Wihan Sandstone	3.95	70.4	3.6	57	87.77	6.56
	Phu Kradung Sandstone	1.72	80.1	14.0	51	53.50	5.30
Plutonic	Tak Granite	4.88	84.5	15.7	56	56.16	6.04
	Granodiorite	4.58	72.5	8.6	59	66.00	6.19
Carbonate	Khao Khad Marble	1.98	36.4	3.2	65	2.90	3.06
	Khao Khad Limestone	1.43	54.6	10.2	55	3.47	3.12
	Khao Khad Travertine	2.09	59.6	6.0	59	2.52	3.05
Sulfate & chloride	Tak Fa Gypsum	0.35	5.6	1.6	34	0.97	2.02
	Tak Fa Anhydrite	1.09	32.2	7.8	26	2.96	3.26
	Maha Sarakham Salt	0.89	22.6	10.6	29	1.38	2.49
Silicate	Pyrophyllite	3.35	80.8	15.1	50	44.13	4.30
	Dickite	1.58	32.3	5.6	45	1.70	2.28
	Skarn	2.49	70.4	10.5	50	34.86	3.55
Volcanic	Khao Kradong Basalt	3.50	79.2	12.8	55	41.34	5.68
	Khao Kradong Vesicular Basalt	3.55	63.9	9.4	54	40.39	5.50
	Khao Yai Rhyolite	3.22	38.5	9.8	50	42.79	4.73
	Khao Yai Andesite	3.49	110.1	13.3	64	46.24	4.50
	Khao Yai Tuff	2.83	41.1	4.3	57	20.54	3.79

4.2. Correlation between CAI and mineral compositions

To consider effect of rock mineral compositions on the wear of stylus pin, Thuro [30] proposes a parameter, called equivalent quartz content (*EQC*), to represent equivalent rock hardness which can be calculated by:

$$EQC = \sum_{i=1}^{n} (W_i \cdot R_i) \tag{5}$$

$$R_i = \exp \cdot [(H_i - 2.12) / 1.05] \tag{6}$$

where *EQC* ranges from 0 – 100%, W_i is mineral weight percent, n is number of minerals, R_i is Rosiwal abrasiveness (%), H_i is hardness of each mineral based on Mohs scale [31], and the constants 2.12 and 1.05 are recommended by Thuro [30]. This approach presumes that tool wear is predominantly a result of the mineral content harder than steel ($H_i = 5.5$), especially quartz ($H_i = 7$). Calculation of *EQC* for Phu Phan sandstone tested here is used as an example below, where their mineral compositions are taken from Table 1.

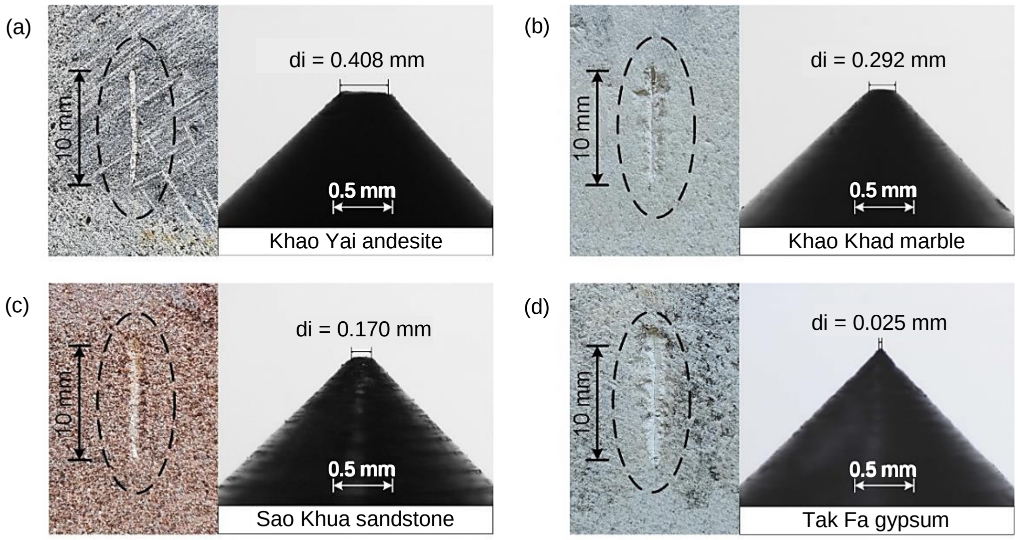

Figure 2 Examples of scratching grooves and wear of stylus tips for some rock types: Khao Yai andesite (a), Khao Khad marble (b), Sao Khua sandstone (c) and Tak Fa gypsum (d).

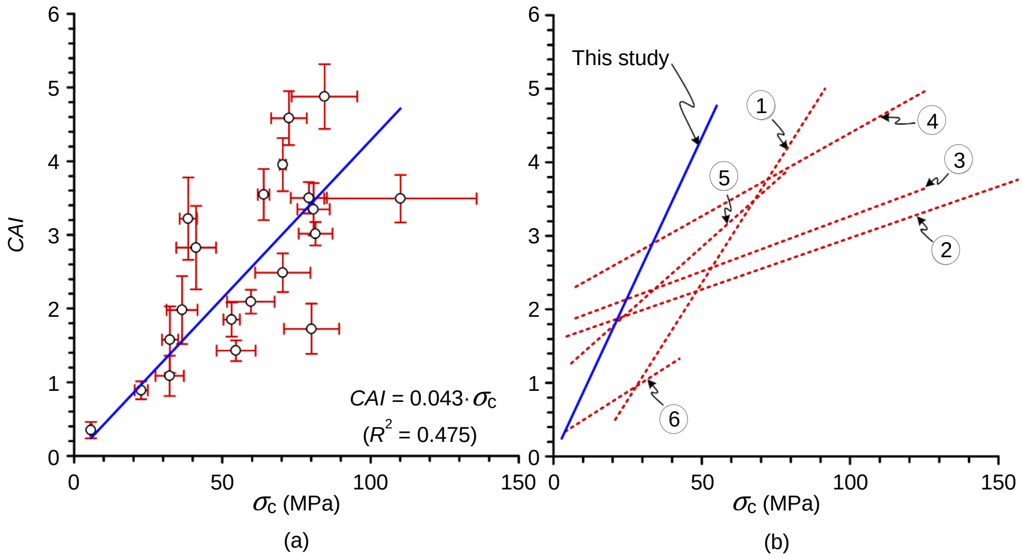

Figure 3 *CAI* as a function of uniaxial compressive strength (a). comparison of the linear correlation of this study with those obtained elsewhere (b). ① Altindag et al. [32], ② He et al. [33] ③-④ Ko et al. [3] ⑤ Hamzaban et al. [34] ⑥ Kotsombat et al. [11].

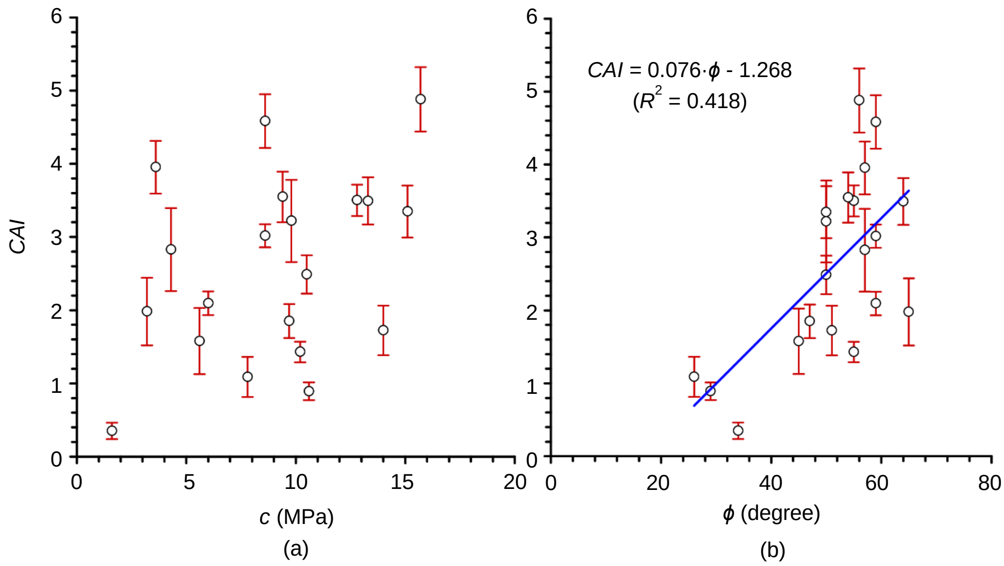

Figure 4 CERCHAR abrasivity index (*CAI*) as a function of cohesion (a), and friction angles (b).

(Quartz) (Kaolinite) (Muscovite) (Albite) (Microcline) (Chlorite)

$$EQC = [(86.13\times100)+(6.27\times1.13)+(1.65\times1.44)+(3.46\times51.08)+(0.60\times51.08)+(1.90\times1.13)]\ /100 \tag{7}$$

$$EQC = 88.31\ \%$$

Similar calculations have been performed for all rocks (Table 3). *CAI*'s are plotted as a function of *EQC* in Figure 5(a). Fair correlation ($R^2 = 0.451$) is obtained between the two parameters when a linear equation is applied. The correlations are improved when clastic and crystalline rocks are analyzed separately. *CAI-EQC* relation for the clastic rock group can be represented by:

$$CAI = 0.051\ EQC - 1.264 \qquad (R^2 = 0.623) \tag{8}$$

For crystalline rock groups:

$$CAI = 0.053\ EQC + 1.227 \qquad (R^2 = 0.870) \tag{9}$$

A new method is proposed here to correlate *CAI* with mineral compositions of rocks. While *EQC* method uses weight percent of minerals composing each rock type, the proposed method considers volumetric percent of the minerals. This would be more sensible and direct approach to represent hardness of the rock surface subjected to stylus pin scratching. This method also uses Mohs scale as a multiplier directly for each mineral without considering the Rosiwal values. The volumetric hardness (H_V) can be calculated by:

$$H_V = [\textstyle\sum_{i=1}^{n} (V_i \cdot H_i)]\ /\ \Sigma V_i \tag{10}$$

$$V_i = W_i\ /\ SG_i \tag{11}$$

Table 3 Empirical constants *a* and *b* for *F*-d_S relation, groove volume, and CERCHAR specific energy.

Rock Group	Rock Type	$F=a$ [1-exp ($-b \cdot d_S$)]		$W = \int_{d_s=0}^{10} F \cdot d_s$ (Joules)	V (mm^3)	CSE (J/mm^3)
		a	*b*			
Clastic	Phu Phan Sandstone	4.603	0.368	33.87	2.71	13.22
	Sao Khua Sandstone	4.265	0.377	31.59	3.99	8.20
	Phra Wihan Sandstone	4.668	0.329	31.77	3.56	9.38
	Phu Kradung Sandstone	3.938	0.375	29.14	2.59	11.64
Plutonic	Tak Granite	3.284	0.440	25.48	1.20	21.97
	Granodiorite	3.155	0.430	24.33	1.24	19.72
Carbonate	Khao Khad Marble	3.534	0.395	26.57	4.55	6.36
	Khao Khad Limestone	3.511	0.425	29.89	2.48	12.91
	Khao Khad Travertine	3.992	0.390	26.97	1.72	16.38
Sulfate & chloride	Tak Fa Gypsum	2.908	0.556	23.88	10.79	2.71
	Tak Fa Anhydrite	4.203	0.306	28.92	4.81	6.53
	Maha Sarakham Salt	2.421	0.257	15.97	3.07	6.28
Silicate	Pyrophyllite	3.276	0.477	25.96	1.98	13.27
	Dickite	2.996	0.524	24.28	3.07	8.69
	Skarn	3.492	0.393	26.22	2.99	9.43
Volcanic	Khao Kradong Basalt	3.588	0.310	24.84	1.70	14.86
	Khao Kradong Vesicular Basalt	5.922	0.223	35.49	1.82	19.63
	Khao Yai Rhyolite	3.772	0.329	26.71	1.85	15.05
	Khao Yai Andesite	3.119	0.447	24.30	1.83	14.09
	Khao Yai Tuff	3.524	0.406	26.72	5.37	5.05

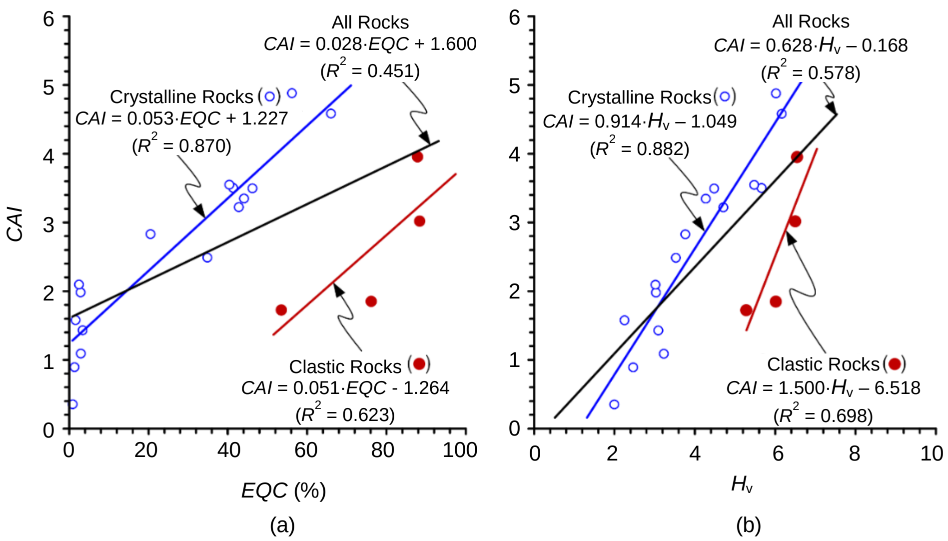

Figure 5 CERCHAR abrasivity index (*CAI*) as a function of equivalent quartz content (*EQC*) (a), and volumetric hardness (H_V) (b).

where V_i is volumetric percent of each mineral (%), W_i is mineral weight percent (%), and SG_i is mineral specific gravity which can be obtained from several mineralogy textbooks [31, 35-37]. Based on the proposed equation above, H_V will range from 1 to 10. Example of H_V calculation for the Phu Phan sandstone is given below. The summation of volumetric percent (ΣV_i) of mineral contents is first calculated:

(Quartz) (Kaolinite) (Muscovite) (Albite) (Microcline) (Chlorite)

$$\Sigma V_i = (86.13/2.66)+(6.27/2.63)+(1.65/2.83)+(3.46/2.63)+(0.60/2.56)+(1.90/2.95) \quad (12)$$

$$\Sigma V_i = 32.38+2.38+0.58+1.32+0.23+0.64 = 37.53\%$$

From Equation (10) H_V can then be obtained as:

(Quartz) (Kaolinite) (Muscovite) (Albite) (Microcline) (Chlorite)

$$H_V = [(32.38\times7)+(2.38\times2.25)+(0.58\times2.5)+(1.32\times6.25)+(0.23\times6.25)+(0.64\times2.25)] /37.53 \quad (13)$$

$$H_V = 6.52$$

H_V results from all tested rocks are plotted in Figure 5(b) where they are correlated with *CAI* using a linear equation. A fair correlation is obtained ($R^2 = 0.578$). Table 2 gives numerical values of the fitting equation. Similar to *CAI-EQC* relation, the correlation between *CAI* and H_V significantly improves when the clastic and crystalline rocks are analyzed separately. For clastic rocks *CAI* can be correlated with H_V by:

$$CAI = 1.500\ H_V - 6.518 \qquad (R^2 = 0.698) \quad (14)$$

For crystalline rock groups:

$$CAI = 0.914\ H_V - 1.049 \qquad (R^2 = 0.882) \quad (15)$$

The improvement of individual correlations for crystalline and clastic rocks suggests that the two rock groups respond differently to the wear of stylus tip (i.e. *CAI*) when hardness of rocks is considered. The diagrams in Figure 5 shows that clastic rocks tend to show higher *EQC* and H_V values than the crystalline rocks do, even though *CAI* values for the two rock groups are within the same range. This results in a low correlation coefficient when only one equation is applied to describe their relation. The high *EQC* and H_V values are due to that grains of the tested sandstones are mainly quartz, albite and anorthite with a combined weight percent between 65% and 90% (see Table 1). Even though these minerals are highly abrasive and abundant in clastic rocks, they tend to have small impact on the wear of stylus tip. This is because the tested surface also contains much softer and lower abrasive minerals (e.g., kaolinite, muscovite, calcite and chloride). The stylus tip ploughs through the softer materials and induces dislodging of the harder grains with a small interaction between the grains and stylus tip. As a result, these highly abrasive grains have small impact on the stylus tip wear. For crystalline rocks, however, the stylus tip likely scratches through all crystals that are more densely packed (regardless of high or low abrasivity). All minerals on the tested surface are, therefore, responsible to the wear of stylus tip.

5. CERCHAR specific energy

Zhang et al. [38] propose a new parameter to correlate with *CAI* and rock strength. It is called CERCHAR specific energy (*CSE*), which can be determined from *CAI* testing but not considering the wear of stylus tip. Such approach has been recently used by several investigators [34, 38]. *CSE* is represened by work done (*W*) applied on stylus pin during scratching to produce groove volume (*V*) on the rock surface. It can be calculated by [38]:

$$CSE = W/V \quad (16)$$

The work done can be calculated by [34]:

$$W = F \cdot d_S \quad (17)$$

where F is lateral force applied on stylus pin and d_S is its travelling distance (10 mm). Here the force can be calculated from torque applied on the crank of CERCHAR apparatus, using Equation (2). Figure 6 gives examples of the measured lateral forces as a function of travelling distance for Khao Kradong basalt (strong rock) and Tak Fa gypsum (soft rock). Dash lines represent force for each scratching and solid lines are their average. Since the force is not constant during scratching. They increase rapidly within the first 3-4 mm. Their increasing rates gradually reduce toward a constant magnitude. A mathematical representation is first developed to describe the evolution of F as a function of d_S. After several trials, an exponential equation is proposed:

$$F = a \cdot [1 - exp \cdot (-b \cdot d_S)] \quad (18)$$

where a and b are empirical constants, depending on rock types. Table 3 gives their numerical values. Very good correlations are obtained for all rocks ($R^2 > 0.9$).

The work done on stylus pin can, therefore, be calculated as:

$$W = \int_{d_S=0}^{10} F \cdot d_S \quad (19)$$

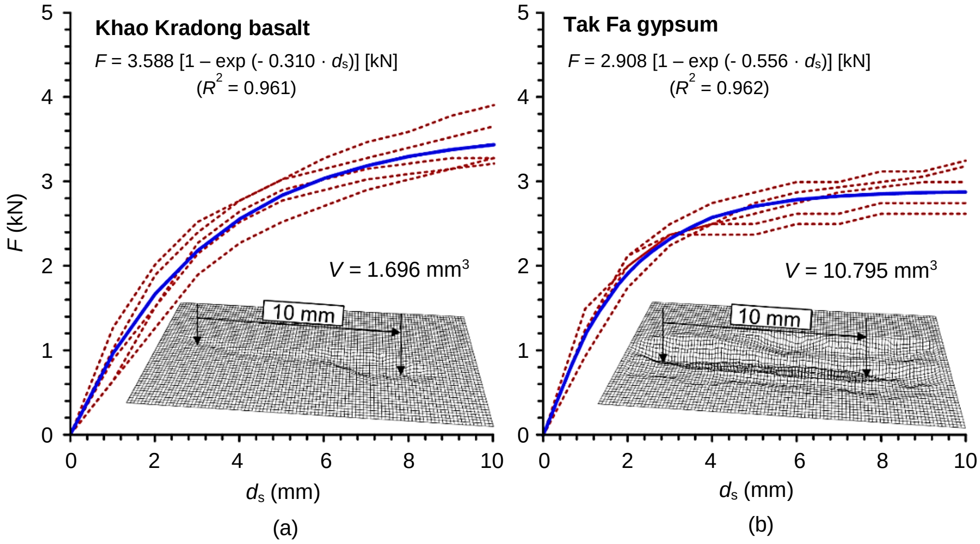

Figure 6 Examples of scratching forces (F) as a function of stylus displacement (d_s) and their laser-scanned groove images for Khao Kradong basalt (a) and Tak Fa gypsum (b). Dash line represents each groove. Solid lines are their average.

The calculation results are given in Table 3. The scratching groove volume (V) can be accurately determined by incorporating its laser scanning profile into SURFER 16.6 software (Golden Software, 2019). Substituting W and V into Equation (16), CERCHAR specific energy can then be obtained. Table 3 gives the average scratch volume and CERCHAR specific energy applied for each rock type. The results suggest that higher energy is required to scratch stronger and higher abrasivity rocks (e.g., granite and granodiorite) as compared to the softer and lower abrasivity rocks (e.g., salt and dickite). The wear of stylus tip as represented here by *CAI* also shows some correlation with the scratched groove volume. High abrasiveness rocks yield smaller groove volume than the lower ones (Figure 7). *CAI* decreases exponentially with increasing groove volume, which can be represented by a potential equation (Figure 7):

$$CAI = k \cdot V^{x} \tag{20}$$

where k and x are empirical constants. Regression analysis gives $k = 5.198$ and $x = -0.960$, where a fair correlation is obtained ($R^2 = 0.462$).

Due to the fact that *CAI* can not correlate well with s_c (as evidenced by results obtained here and elsewhere in Figure 3, some investigators [38] have attempted to correlate *CSE* with s_c. This is because *CSE* is derived from the applied stylus force and groove volume, where both parameters are governed by mineral compositions of the rock. In addition, *CSE* does not involve the wear of stylus pin tip (i.e. *CAI*). The compressive strength is also depended on mineral compositions and physical characteristics of the rocks. Such approach is adopted for Thai rocks selected in this study. Figure 8 plots *CSE* as a function of s_c and *CAI*. Only fair correlation ($R^2 = 0.436$) is again shown between *CSE* - s_c relation based on a linear equation (Figure 8(a)):

$$CSE = 0.136 \cdot s_c + 3.817 \qquad (\text{J/mm}^3) \tag{21}$$

Slightly better correlation is obtained between *CSE* and *CAI*. A linear equation can describe their positive correlation, showing $R^2 = 0.569$ (Figure 8(b)):

$$CSE = 3.204 \cdot CAI + 3.413 \qquad (\text{J/mm}^3) \tag{22}$$

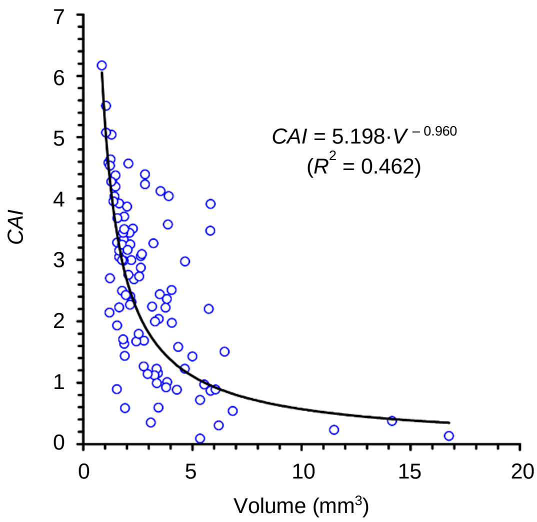

Figure 7 *CAI* as a function of groove volume for all rock types.

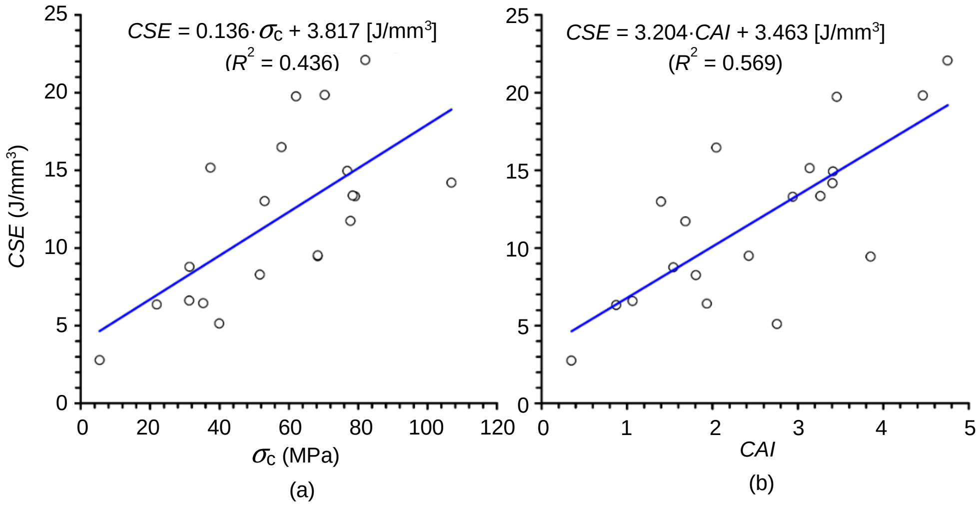

Figure 8 CERCHAR specific energy (*CSE*) as a function of uniaxial compressive strength (a), and of CERCHAR abrasivity index (b).

6. CERCHAR specific energy and volumetric hardness

An attempt is further made to correlate CERCHAR specific energy with an alternative parameter obtained from *CAI* testing. Suggesting by the good correlation between *CAI* and volumetric hardness (H_V) given in section 4 (Figure 5), particularly when crystalline and clastic rock groups are correlated separately, *CSE* is presented as a function of H_V in Figure 9(a). Even though a positive linear relation is clearly shown between the two parameters, their correlation is relatively poor (R^2 = 0.332):

$$CSE = 2.020 \cdot H_V + 2.884 \qquad (J/mm^3) \qquad (23)$$

It is postulated that the volumetric hardness of crystalline and clastic rocks may respond differently to the scratching energy. As discussed earlier that for clastic rocks the soft minerals are the main factors affecting the wear of stylus tip. To further investigate this issue, a modified volumetric hardness (H_V^*) is proposed to incorporate into the CERCHAR specific energy and volumetric hardness relation. The calculation of the modified hardness (H_V^*) is similar to those of Equations (12) and (13) for Phu Phan sandstone, except that only soft minerals are taken into consideration (i.e., Kaolinite, microcline and chlorite). Figure 9(b) shows *CSE* - H_V relation with H_V^* for clastic rocks, and the original H_V for crystalline rocks. *CSE* increases linearly with volumetric hardness with R^2 = 0.605.

$$CSE = 3.181 \cdot H_V^* - 0.176 \qquad (J/mm^3) \qquad (24)$$

Based on the modification above, the *CSE*-H_V correlation coefficients have increased from 0.332 (Figure 9(a)) to 0.605 (Figure 9(b)) supporting that the soft and low abrasive minerals in clastic rocks are the main factor dictating how much energy is required to scratch the rocks, and how much the stylus tip is worn.

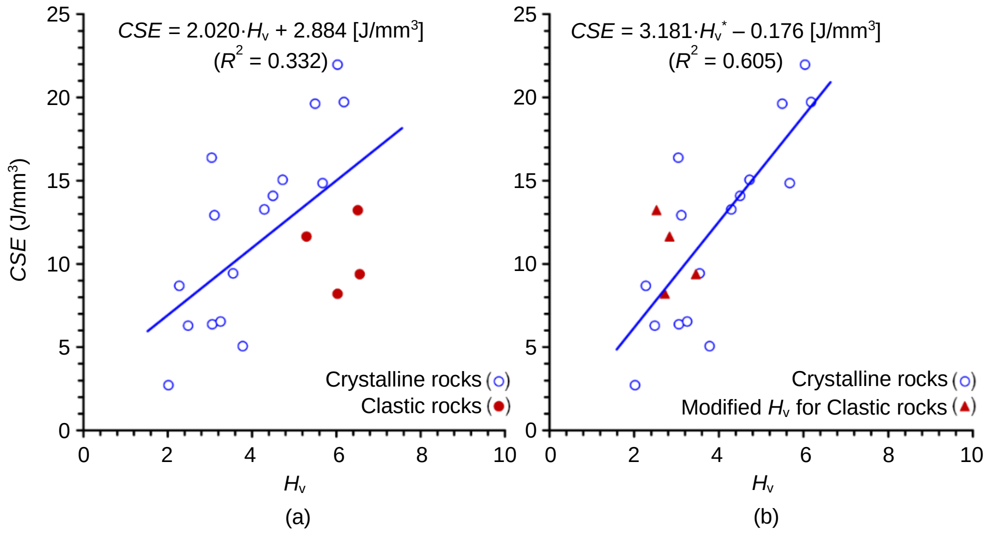

Figure 9 CERCHAR specific energy (*CSE*) as a function of volumetric hardness (H_V) for both crystalline and clastic rocks (a), and for both rock groups with modified H_V for clastic rocks (b).

The modified volumetric hardness (H_V^*) can not be applied to the *CAI*-H_V relation (Figure 5) because quartz contents do affect the wear of stylus tip (*CAI*) even for clastic rocks. As a result, they should not be taken out when the volumetric hardness of rock is calculated to correlate with *CAI*.

7. Discussions

Several investigators (as quoted in Figure 3) have recognized that only fair correlations can be obtained between uniaxial compressive strength and CERCHAR abrasivity index. Such correlation, however, has been widely performed. This is primarily because the rock strengths are readily available for most geological and mining engineering projects. Some investigators [18, 20, 21] can obtain their correlation coefficients of greater than 0.8. They however compare only few rock types with similar characteristics (e.g., sandstone, siltstone). In general rock strengths and *CAI* cannot be correlated well because the two parameters are derived from different mechanisms of failure or breakage. The failure of uniaxial test specimen is induced by the initiation and propagation of microcracks, fissures, intercrystalline boundaries, pore spaces and cleavage. When the applied stress reaches an ultimate value, these defects are connected, and compressive shear failure is induced [39]. The wear of stylus tip (*CAI*) is produced by shearing process controlling by abrasiveness and hardness of the minerals composing rock which may not have a direct relation with their strength. The mechanisms induce the wear of stylus tip are complex. The stress distribution in rock at and around the stylus tip also shows very high gradient under macroscopic scale, as demonstrated by numerical simulations by Balani, et al. [9].

Correlation between *CAI* and mineral compositions of rocks (Figure 5) gives a more promising approach to predict the wear of stylus tip, as compared to the *CAI*-s_c relations. For *CAI-EQC* and *CAI*-H_V relations, the improvement of their correlation coefficients by analyzing clastic and crystalline rocks individually suggests that *CAI* is governed not only by hardness of minerals composing rocks, but also by rock characteristics. No attempt has been made here to correlate *CAI* with s_c, c and f under different rock classifications (i.e., crystalline and clastic). This is primarily because these mechanical properties do not have direct relation with rock textures and mineral compositions.

The volumetric hardness (H_V) proposed in this study has a clear advantage over the *EQC* method when they are correlated with *CAI*. For soft rocks *EQC* can not distinguish the different responses of mineral compositions to *CAI* for soft rocks. As demonstrated in Figure 5(a), these soft rocks include those containing low hardness minerals, for example, travertine, dickite, salt and gypsum. This is because *EQC* uses multipliers given by Rosiwal abrasiveness (R_i) which places a main emphasis on hard minerals, as R_i = 100 (%) for quartz. R_i values are decreased rapidly toward soft minerals with hardness low than 7. The volumetric hardness proposed here, however, simply uses Mohs scale hardness as multipliers to the minerals. The Mohs scale has been designed with, more or less, equal intervals for mineral hardness variation. Hence, H_V can distinguish the equivalent rock hardness gradually and continuously from low to high ranges of *CAI* better than *EQC*. This is, particularly, useful for soft to medium strong rocks that are commonly found in mining and construction projects in Thailand.

It is recognized here that *CAI* is also affected by grain (crystal) size and shape, as experimentally shown by Er and Tuğrul [19] and Yaralı et al. [23]. These factors can not be analyzed in this study due to the narrow range of rock characteristics and limited number of rock types.

The concept of CERCHAR specific energy (*CSE*) is relatively new. It excludes the wear of stylus tip while deriving the relation between the applied mechanical energy of stylus pin and the mechanical properties and characteristics of rock. Only fair correlation has been obtained here for *CSE*-s_c relation (Figure 8). This may be due to the different mechanisms that induce failure and breakage between the two tests, as discussed above for *CAI*-s_c relation. *CSE* can correlate well with H_V, only if the volumetric hardness for clastic rocks is modified by considering only hardness of soft minerals (Figure 9(b)). This supports the previous postulation that clastic and crystalline rocks should be analyzed separately, not only for *CAI* - H_V relation, but also for *CSE*-H_V relation.

CAI and *CSE* have been derived from different parameters of testing. Both are useful for the rock excavation operation. *CAI* relates to the wear of excavation tools. *CSE* relates to the energy (force and distance) required to excavate a unit volume of rocks. This is why both parameters remain important and deserve further experimental investigation.

To correlate *CAI* with machine and tool wear during construction and excavation, practitioners and operators need to keep record and documentation on the rock characteristics and operating parameters during excavation process. These include, for example, rock type, mineral compositions, rotational speeds, weight on bits, penetration rates, and temperatures. The more accurate and detailed records, the better correlation between the tool wear and the *CAI* obtained from laboratory can be achieved.

8. Conclusions

In an attempt to determine the wear of excavation tools as affected by rock characteristics, CERCHAR abrasivity index (CAI) tests have been performed to correlate the results with various aspects of mechanical and mineral properties of twenty rock types commonly encountered in mining and construction projects in Thailand. Conclusions drawn from this study can be summarized as follows.

Only fair correlation (R^2 = 0.473) is obtained between *CAI* and uniaxial compressive strengths of Thai rocks selected in this study, primarily due to the differences of mechanisms governing the results obtained from the two tests, which agrees with research results obtained elsewhere. In addition, due to the differences of failure mechanisms only fair linear correlation is also shown between *CAI* and rock friction angle, while no correlation between *CAI* and rock cohesion has been found.

A new parameter called "volumetric hardness - H_V" is developed from this study to correlate *CAI* with mineral compositions of rocks. Their correlation is notably better than those obtained from the widely used equivalent quartz content - *CAI* relation, as it can clearly distinguish the differences of hardness of minerals composing soft to medium strong rocks (Figure 5). This is because *EQC* places main emphasis on the minerals harder than quartz, while the proposed H_V considers volume of all minerals composing rocks. This study reveals also that *CAI-EQC* and *CAI*-H_V relations can be further improved when clastic and crystalline rocks are analyzed separately in the regression. This is presumably because the grain (quartz and felspar) contents in clastic rocks tested here have small impact on the stylus tip which mean that the stylus can easily plough through much softer cementing materials.

CAI-H_V relation has a clear advantage over *CAI-EQC* relation for soft to medium strong rocks. Both relations nevertheless perform equally well for very strong rocks, as suggested by the diagrams shown in Figure 5. It should be noted that *EQC* and H_V require accurate determination of weight percents of minerals composing rocks, such as those obtained here from X-ray diffraction analysis. Visual observation of hand specimens or conventional petrographic study may not provide adequate results. The diagrams shown in Figures 3 through 5 suggest also that the wear of stylus tip (*CAI*) relates more to the mineral compositions of rocks than to the rock mechanical properties.

This study determines scratching volume by laser-scanning technique supported by 3-D graphic software (SURFER 16.6). This gives very accurate results (to the nearest 0.01 mm^3) which become useful for the CERCHAR specific energy calculation. Such technique has never been employed elsewhere. The accurate scratch volume (*V*) also leads to a new finding of *CAI-V* relation as shown by negative exponential equation in Figure 7. Such relation has never been found or mathematically determined by other investigators.

As discussed above *CSE* has been derived from the test parameters different from those of *CAI*. It involves the energy required to remove a unit volume of rocks which mainly relates more to the volume of soft minerals rather than to those of the harder ones. Such differences represent the main characteristics of the clastic rocks tested here. The modified volumetric hardness (H_V^*), therefore, gives a better correlation with *CSE*, as shown in Figure 9. Care should be taken to apply H_V^* to other clastic rocks. It is valid only if the cementing minerals are much softer than the grain minerals. If they have comparable hardness, application of original H_V is more appropriate.

CSE linearly increases with *CAI* (Figure 8(b)), suggesting that rocks with high abrasivity require higher energy to cut, and yield lower excavated volume than those with lower abrasivity.

The findings obtained from this study are applicable to other soft to medium strong rocks. In particular, the approach of analyzing clastic and crystalline rocks separately is highly desirable when the effect of mineral compositions on *CAI* and *CSE* is investigated.

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10. References

[1] Thuro K, Käsling H. Classification of the abrasiveness of soil and rock. Geomech Tunn. 2009;2(2):179-88.
[2] Prieto LA. The CERCHAR abrasivity index's applicability to dredging rock. Proceedings of Western Dredging Association (WEDA XXXII) Technical Conference and Texas A&M University (TAMU 43) Dredging Seminar; 2012 Jun 10-13; San Antonio, Texas. p. 212-9.
[3] Ko TY, Kim TK, Son Y, Jeon S. Effect of geomechanical properties on Cerchar Abrasivity Index (CAI) and its application to TBM tunnelling. Tunn Undergr Space Technol. 2016;57:99-111.
[4] ASTM. ASTM D7625-10: Standard test method for laboratory determination of abrasiveness of rock using the CERCHAR method. Philadelphia: American Society for Testing and Materials; 2010.
[5] Alber M, Yaralı O, Dahl F, Bruland A, Käsling H, Michalakopoulos TN, et al. ISRM Suggested method for determining the abrasivity of rock by the CERCHAR abrasivity test. Rock Mech Rock Eng. 2014;47(1):261-6.
[6] ASTM. ASTM D7625-22: Standard test method for laboratory determination of abrasiveness of rock using the CERCHAR abrasiveness index method. Philadelphia: American Society for Testing and Materials; 2010.
[7] Al-Ameen SI, Waller MD. The influence of rock strength and abrasive mineral content on the Cerchar Abrasive Index. Eng Geol. 1994;36(3-4):293-301.
[8] Plinninger R, Käsling H, Thuro K, Spaun G. Testing conditions and geomechanical properties influencing the CERCHAR abrasiveness index (CAI) value. Int J Rock Mech Min Sci. 2003;40(2):259-63.
[9] Balani A, Chakeri H, Barzegari G, Ozcelik Y. Investigation of various parameters effect on CERCHAR abrasivity index with PFC3D modeling. Geotech Geol Eng. 2017;35(6):2747-62.
[10] Hamzaban MT, Karami B, Rostami J. Effect of pin speed on Cerchar abrasion test results. J Test Eval. 2019;47(1):121-39.
[11] Kotsombat T, Thongprapha T, Fuenkajorn K. Scratching rate effects on CERCHAR abrasiveness index of sandstones. Proceedings of Academicsera International Conference; 2020 Sep 22-23; Chiang Mai, Thailand.
[12] Aydın H. Investigating the effects of various testing parameters on Cerchar abrasivity index and its repeatability. Wear. 2019;418-419:61-74.
[13] Käsling H, Thuro K. Determining rock abrasivity in the laboratory. ISRM International Symposium – EUROCK; 2010 Jun 15-18; Lausanne, Switzerland. Lausanne: International Society for Rock Mechanics and Rock Engineering; 2010. p. 1-4.
[14] Yaralı O, Duru H. Investigation into effect of scratch length and surface condition on Cerchar abrasivity index. Tunn Undergr Space Technol. 2016;60:111-20.
[15] Ozdogan MV, Deliormanli AH, Yenice H. The correlations between the CERCHAR abrasivity index and the geomechanical properties of building stones. Arab J Geosci. 2018;11(20):604.
[16] Sirdesai NN, Aravind A, Panchal S. Impact of rock abrasivity on TBM cutter-discs during tunnelling in various rock formations. In: Kalamkar V, Monkova K, editors. Advances in Mechanical Engineering. Singapore: Springer; 2021. p. 527-34.
[17] Yasar S, Yilmaz AO. Tool wear prediction with different models for medium strength rocks. Proceedings of the 13th International Conference Underground Construction Prague 2016; 2016 May 23-25; Prague, Czech. p. 1-10.
[18] Capik M, Yilmaz AO. Correlation between CERCHAR abrasivity index, rock properties, and drill bit lifetime. Arab J Geosci. 2017;10:1-12.
[19] Er S, Tuğrul A. Correlation of physico-mechanical properties of granitic rocks with CERCHAR abrasivity index in Turkey. Measurement. 2016;91:114-23.
[20] Teymen A. The usability of Cerchar abrasivity index for the estimation of mechanical rock properties. Int J Rock Mech Min Sci. 2020;128:104258.
[21] Deliormanlı AH. CERCHAR abrasivity index (CAI) and its relation to strength and abrasion test methods for marble stones. Constr Build Mater. 2012;30:16-21.
[22] Suana M, Peters T. The CERCHAR abrasivity index and its relation to rock mineralogy and petrography. Rock Mechanics. 1982;15:1-8.
[23] Yaralı O, Yaşar E, Bacak G, Ranjith PG. A study of rock abrasivity and tool wear in coal measures rocks. Int J Coal Geol. 2008;74(1):53-66.
[24] West G. Rock abrasiveness testing for tunnelling. Int J Rock Mech Min Sci Geomech Abstr. 1989;26(2):151-60.
[25] Aydın H, Yaralı O, Duru H. The effects of specimen surface conditions and type of test apparatus on Cerchar Abrasivity Index. Karaelmas Sci Eng J. 2016;6(2):293-8.
[26] Barton N, Choubey V. The shear strength of rock joints in theory and practice. Rock mechanics. 1977;10:1-54.
[27] Budynas RG, Nisbett JK, Shigley JE. Shigley's Mechanical Engineering Design. 9th ed. New York: McGraw-Hill; 2011.

[28] ASTM. ASTM D7012-14e1: Standard test methods for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures. West Conshohocken: American Society for Testing and Materials; 2014.
[29] Rostami K, Hamidi JK, Nejati HR. Use of rock microscale properties for introducing a cuttability index in rock cutting with a chisel pick. Arab J Geosci. 2020;13:1-12.
[30] Thuro K. Drillability prediction: geological influences in hard rock drill and blast tunnelling. Geol Rundsch. 1997;86:426-38.
[31] Klein C. Manual of Mineral Science. 22nd ed. Hoboken: John Wiley & Sons; 2002.
[32] Altindag R, Sengun N, Sarac S, Mutluturk M, Guney A. Evaluating the relations between brittleness and Cerchar abrasion index of rocks. Proceedings of the ISRM Regional Symposium - EUROCK 2009; 2009 Oct 29-31; Cavtat, Croatia. p. 195-200.
[33] He J, Li S, Li X, Wang X, Guo J. Study on the correlations between abrasiveness and mechanical properties of rocks combining with the microstructure characteristic. Rock Mech Rock Eng. 2016;49:2945-51.
[34] Hamzaban MT, Memarian H, Rostami J. Determination of scratching energy index for CERCHAR abrasion test. J Min Environ. 2018;9(1):73-89.
[35] Haldar SK, Tišljar J. Introduction to mineralogy and petrology. Amsterdam: Elsevier; 2014.
[36] Nesse WD. Introduction to mineralogy. New York: Oxford University Press; 2000.
[37] Perkins D. Mineralogy. 3rd ed. Harlow: Pearson Education Limited; 2013.
[38] Zhang G, Konietzky H, Frühwirt T. Investigation of scratching specific energy in the Cerchar abrasivity test and its application for evaluating rock-tool interaction and efficiency of rock cutting. Wear. 2020;448-449:203218.
[39] Jaeger JC, Cook NGW, Zimmerman R. Fundamentals of rock mechanics. 4th ed. Oxford: Blackwell; 2007.