CHAPTER II
LITERATURE REVIEW

This chapter gives a summary of literature review to understand the rock abrasiveness, CERCHAR testing researches and joint aperture and spacing.

2.1 Rock abrasiveness

The abrasiveness of rock is a significant factor affecting excavation tools during rock excavation. This factor results in loss of considerable costs due to wear and tear on the excavation tools. Various rock characteristics can influence the performance of excavation tools on the work site. It is crucial to gather information about the rock's characteristics in the area before commencing work (Thuro and Käsling, 2009). Rock abrasiveness depends on the types of rock and the presence of abrasive minerals within it. Consequently, various tests are developed and actively utilized for rock identification (Ghasemi, 2010).

Intensity and wear rate depend on several factors simultaneously acting in the interaction between the indenter and the rock (Labaš, Krepelka and Ivaničová, 2012). The most crucial factors include:

1. Types and properties of friction surfaces.
2. Operation regime of the cutting indenter (tool).
3. Properties of environment where the indenter operates.

2.2 CERCHAR testing

The CERCHAR test consists of three types: type one the original test developed by the CERCHAR center, type two version produced at the Colorado School of Mines (CSM) in the mid-1980s, and type three involved modification of (West's,1989) CERCHAR test (Rostami, Ozdemir, Bruland, & Dahl, 2005) (Figure 2.1). Type one and three are similar, as described by Plinninger, Käsling, Thuro, and Spaun (2003).

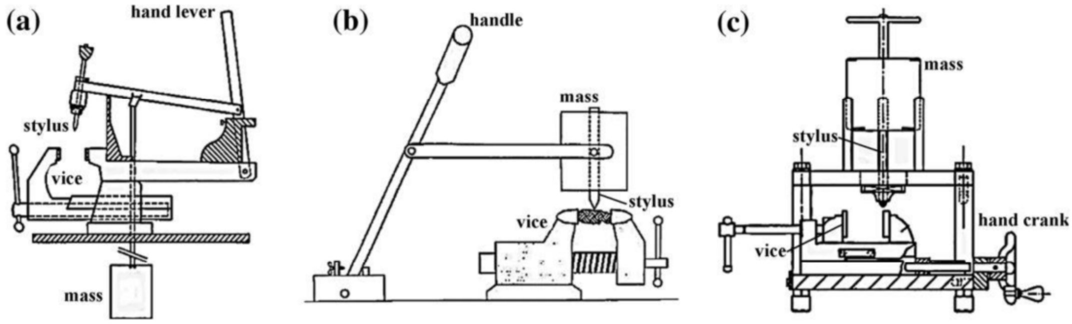


Figure 2.1 CERCHAR testing devices, CERCHAR Centre (a), CSM (b), West (c) (Rostami, Ozdemir, Bruland and Dahl, 2005).

The CERCHAR abrasivity test is a standardized procedure used to assess the abrasiveness or the abrasive potential of rocks and other geological materials (ASTM D7625-22). The CERCHAR scraping tool perpendicular to the specimen. The force applied is measured under vertical constant force of 70 N. Stylus scratches a groove of 10 mm in length on the rock surface. After scratching the wear on the stylus tip is measured in 0.1 mm units. The test apparatus includes a steel stylus with a Rockwell hardness of HRC 55, positioned perpendicular to the rock surface. Five individual tests are conducted on each specimen. CAI is calculated based on the average wear from the five tests. For saw-cut surfaces, the CAI is normalized to account for differences between saw-cut and natural rough surfaces.

2.2.1 Testing length

A longer length will cause more wear and tear. For better CAI estimation, multiple tests are performed on the same specimen with different test lengths (Plinninger et al., 2003) Of the 70% of pin wear occurring during the first millimeter of the test length, approximately 85% of the CAI occurs after 2 mm, and only 15% of the change in CAI is achieved at 8 mm, as shown in Figure2.2 (Al-Ameen and Waller, 1994).

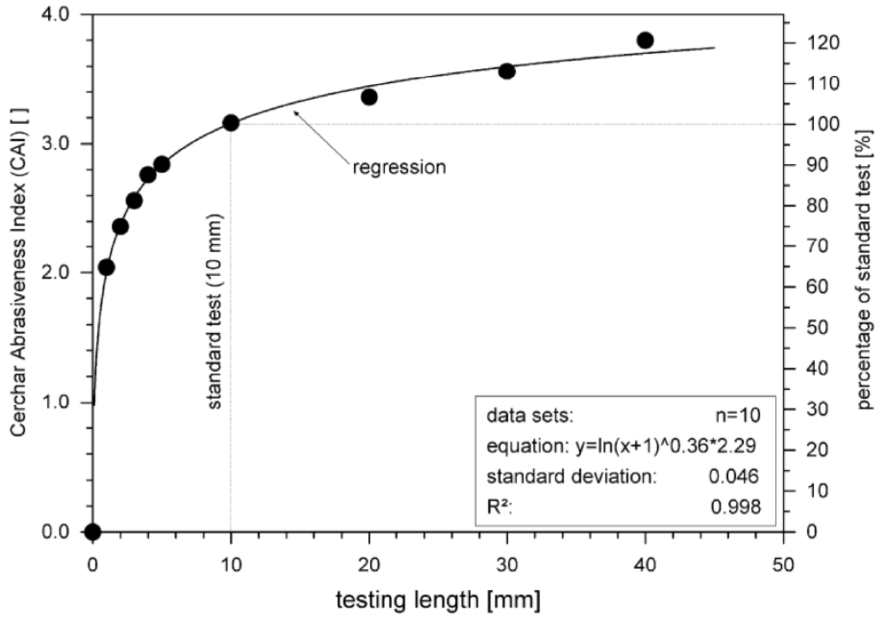


Figure 2.2. CAI versus length (Plinninger et al., 2003).

This method of extending the scratch length however is not beneficial. The deviation in CAI caused by changes in scratch length is not very significant when the variation in test length is kept between ± 0.5 mm (Plinninger, et al., 2003).

Scratches with lengths between 2 mm and 20 mm in 2 mm increments are analyzed separately by Yaralı and Duru (2016). It depends on the type of hardness of the stylus and various surface conditions (saw and rough cutting) and is summarized in Figure 2.3.

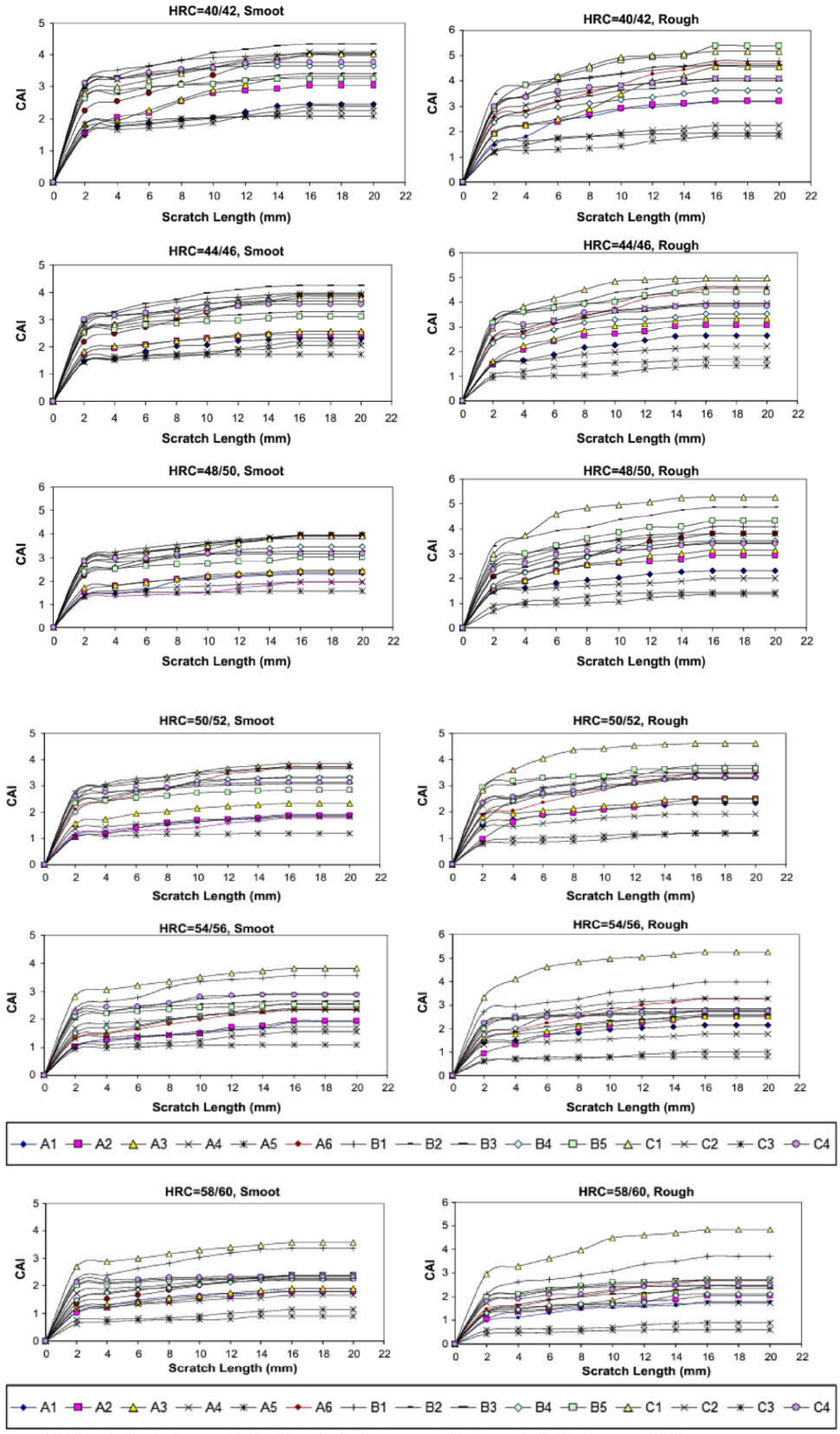
The test stylus wear does not end in a slide path of 10 mm, while the test stylus wear ends at a slide length of about 16 mm, and levels decrease. CAI is shown within the initial 2 mm of the scratch length. This continues to rise at an increasing rate until it reaches 16 mm and then decreases (Yarali and Duru, 2016). The evaluation results of the pin hardness and surface condition tests are shown in Table 2.1 and Figure 2.3.

Table 2.1. Evaluation results of pin hardness and surface condition tests for different scratch lengths (Yaralı and Duru, 2016).

Sample surface		Scratch length (mm)						
		2		10		15[a]		20
		(CAI)	(%)	(CAI)	(%)	(CAI)	(%)	(CAI)
Metamorphic rocks	SD	0.70	7.69	0.93	3.29	1.03	0.63	1.05
Sawn-cut	Avg	2.27	78.42	2.75	93.50	2.93	99.10	2.96
Rough	SD	0.93	6.44	1.45	1.00	1.52	0.22	1.53
	Avg	2.14	65.37	3.09	93.81	3.26	99.19	3.29
Smooth and rough	SD	0.81	6.57	1.18	1.54	1.27	0.38	1.29
	Avg	2.21	71.80	2.92	93.74	3.10	99.16	3.13
Sedimentary rocks	SD	0.26	6.17	0.49	4.18	0.56	0.54	0.57
Sawn-cut	Avg	1.45	63.01	2.01	86.37	2.28	97.79	2.33
Rough	SD	0.40	8.48	0.72	4.28	0.83	0.45	0.86
	Avg	1.45	58.60	2.16	84.99	2.48	97.70	2.54
Smooth and rough	SD	0.32	7.21	0.59	4.04	0.68	0.31	0.70
	Avg	1.45	60.63	2.09	85.62	2.38	97.72	2.43
Igneous rocks	SD	0.17	6.83	0.34	0.65	0.37	0.20	0.37
Sawn-cut	Avg	2.38	73.57	3.06	94.23	3.22	99.26	3.25
Rough	SD	0.46	6.53	0.38	2.32	0.42	0.62	0.43
	Avg	2.37	64.44	3.32	90.83	3.60	98.44	3.66
Smooth and rough	SD	0.81	6.57	1.18	1.54	1.27	0.38	1.28
	Avg	2.20	71.80	2.92	93.73	3.10	99.16	3.12

SD: Standard Deviation; Avg.: Average.

[a] Average of 14 and 16 mm scratch length.



A1 :Fine Grain Sandstone, A2 :Medium Grain Sandstone, A3 :Coarse Grain Sandstone, A4 :Limestone, A5 :Dolomitic Limestone,A6 :Quartz Sandstone, B1 :Granite, B2 :Diabase, B3:Porphyritic Basalt Andesite, B4 :Porphyritic Andesite, B5 :Basalt, C1 :Quartzite, C2 :Quartz-Schist, C3 :Marble, C4 :Metadiabase

Figure 2.3. Results of pin hardness and surface condition tests (Yarali and Duru, 2016).

2.2.2 Stylus hardness

Michalakopoulos, Anagnostou, Bassanou and Panagiotou, (2005) tests 68 specimens with HRC 40 and HRC 55 and find that high stylus hardness shows the lower the CAI value corresponding to stylus hardness. CAI values exhibit substantial variation in response to changes in stylus hardness, rock type, and the geological origin of rocks. Generally, the average CAI decreases as the stylus hardness increases for all specimen hardness (Aydın, 2019). Yaralı and Duru, (2016) study the coefficient of variance (CV) or relative standard deviation to assess the distribution of CAI values in relation to stylus hardness. They use 6 stylus pin with Rockwell hardness ranging from HRC 40-42 to HRC 58-60. The results, shown in Figure 2.4, indicate that on sawn surfaces, the CV values for CAI ranged from 21.22 to 29.30, with the lowest CV values observed at HRC 54/56 for stylus hardness. On rough surfaces, the CV values ranged from 30.02 to 38.69, with the lowest values also occurring at HRC 54/56. The results suggest that the least variance in CAI measurements is dependent of stylus hardness, especially on sawn surfaces, and the significant of both stylus hardness and surface condition in minimizing measurement variance is significant.

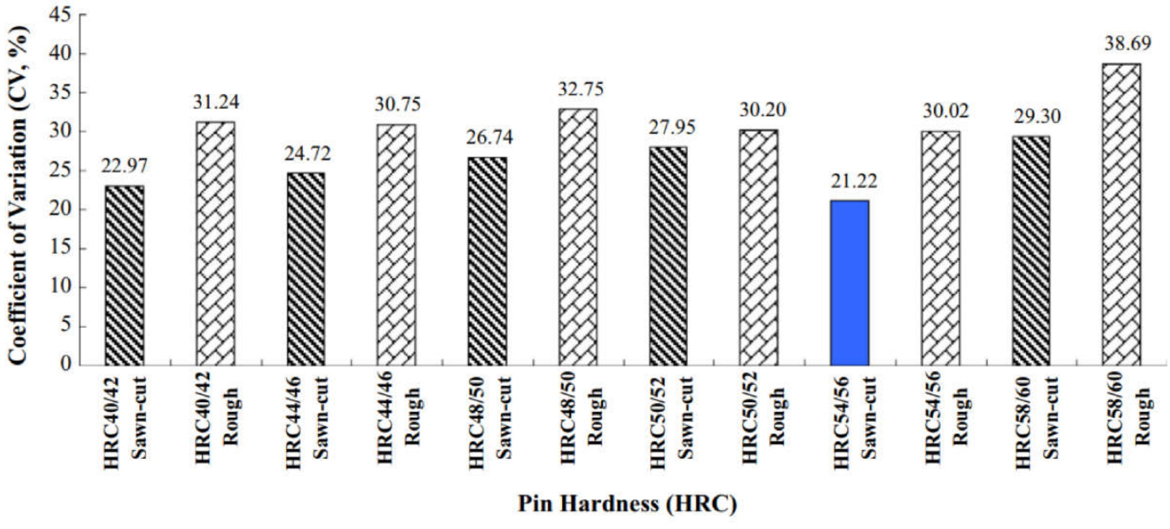


Figure 2.4 Coefficient of variation of CAI values measurement depends on pin hardness and surface condition of various samples (Yarali and Duru, 2016).

2.2.3 Material removal volume

Numerous researchers have examined the volumetric parameters involved in CERCHAR testing, with particular attention to both the wear volume of the stylus and the groove volume generated on the rock surface during the scratching process.

The wear volume of the stylus is typically calculated using the geometric formula for a cone, where the radius and height of the cone are taken as half the width of the worn stylus tip, as illustrated in Figure 2.5(a) Hamzaban, et al., (2019); Zhang and Konietzky, (2020). Conversely, the groove volume is determined by integrating the trapezoidal cross-sectional area along the scratching length, as depicted in Figure 2.5(b) Hamzaban, et al., (2019).

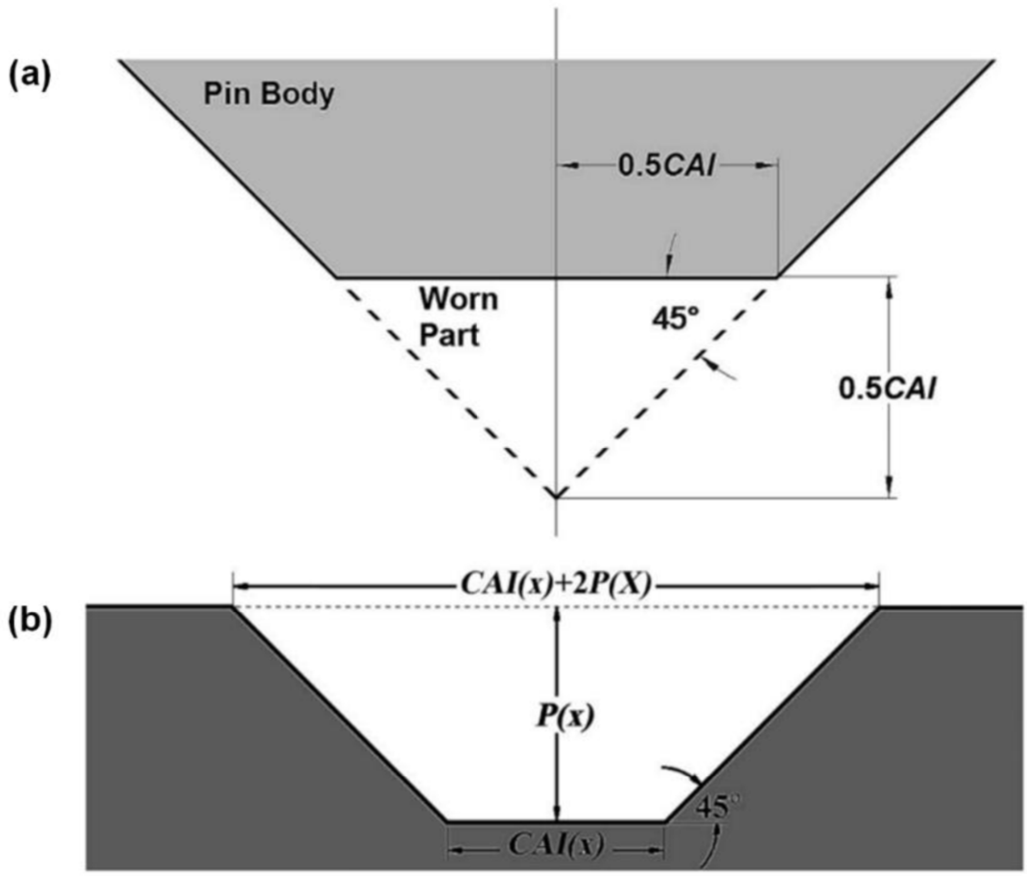


Figure 2.5 Geometry of worn pin tip (a) and cross section of scratch on sample Surface at a distance of x from beginning of motion path (b) (Hamzaban, et al., 2019).

The CAI is related to mean groove volume (V) as described by Kathancharoen and Fuenkajorn, (2023) who test 21 rocks, Their results are divided into two categories: clastic and crystalline rocks, which gives the CAI-V correlation curves as shown in Figures 2.6(a) and 2.6(b), and can be represented by the following equation.

$$CAI = \alpha \cdot (V)^{\beta} \quad (2.1)$$

where α and β are empirical constants that determine the relationship between CAI and V. An exception is porous basalts, which shows the opposite trend, where CAI increasing with increasing mean pore volume, possibly due to surface roughness that results in void formation. These rocks also have higher porosity, especially when compared to other rocks, except for clastic rocks. When grouping the rocks, crystalline rocks show a slightly stronger correlation between CAI and mean groove volume (R^2 of 0.452) as compared to the combined analysis of all rock types (R^2 of 0.391). In contrast, clastic rocks display a weak correlation, with R^2 of 0.039, indicating minimal association between mean groove volume and CAI in this group.

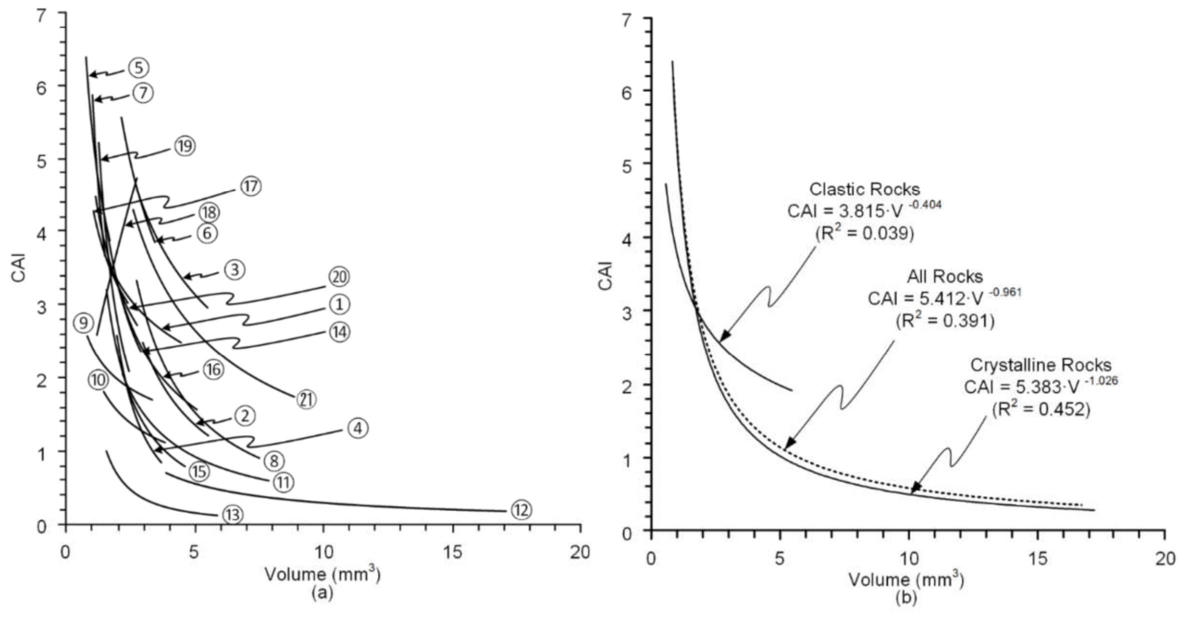


Figure 2.6 Correlation between CAI value and mean groove volume separated by rock types (a) and rock groups (b) (Kathancharoen and Fuenkajorn, 2023).

To further quantify the volume of material removed during the scratching process, a scanning electron microscope (SEM) is employed to analyze the rock surface post-scratch (Zhang and Konietzky, 2020). These volume parameters are crucial for the calculation of the scratch volume to wear ratio (SVWR) (Hamzaban et al., 2019) and the CERCHAR abrasion ratio (CAR), Zhang and Konietzky, (2020); Zhang, Konietzky, Song, and Zhang, (2020).

2.3 Rock properties

Rocks contain many factors that affect CAI values, including mineral compositions, hardness, grain size, and mechanical properties such as rock strength and hardness. (Beste, Lundvall and Jacobson, 2004).

2.3.1. Physical properties

The mineral compositions of a rock are related to its abrasiveness. Grain sizes of crystalline rocks with sharp edges are especially abrasive, (Feniak, 1944). The CAI value for a rough surface is higher than for a sawn cut surface. Hard rocks can be more abrasive than soft rock, (Rostami, et al. 2013). Suana and Peters, (1982) investigate the relationship between CERCHAR abrasivity index (CAI) and mineralogical and petrographic characteristics of rocks. Their study shows that grain size does not significantly influence the CAI, provided that the grain size falls within the range of 50 to 1000 microns. However, when grain sizes exceed 1 mm, a larger number of tests than the standard protocol recommends may be required to obtain a more accurate mean value. Despite this, their findings showed no discernible dependency of CAI values on grain size, with no significant variation observed between conducting 5 and 10 tests within the analyzed grain size range (Lassnig, Latal, and Klima, 2008). Kathancharoen and Fuenkajorn (2023) explain that mineral compesitions relate to volumetric hardness better than EQC. Both parameters have a positive linear relationship with CAI, as EQC and HV increase, CAI also increases. The correlation between CAI and EQC is moderate for all rocks (R^2 = 0.413), but stronger in specific rock groups: Clastic rocks (R^2 = 0.623) and Crystalline rocks (R^2 = 0.877 the highest correlation) (Figure 2.7). The correlation between CAI and HV is even stronger than the

EQC correlation. Clastic rocks (R^2 = 0.623), Crystalline rocks (R^2 = 0.893) and for all rocks (R^2 = 0.591)

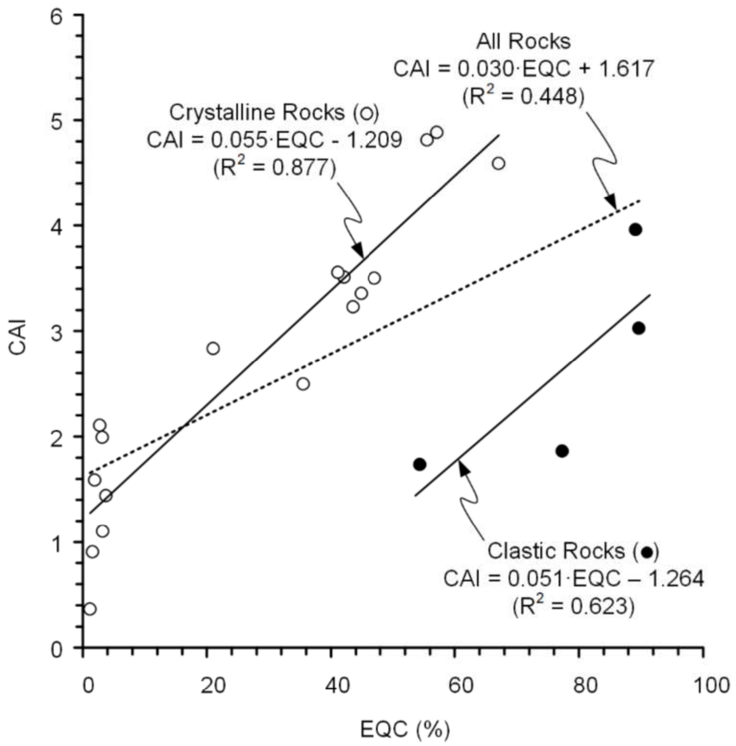


Figure 2.7 Correlation between CAI value and equivalent quartz contents (EQC) (Kathancharoen and Fuenkajorn, 2023).

When the HV of a rock is lower, the CAI also remains low or even zero, with an HV value of approximately 0.4 when the CAI is zero (Figure 2.8). This trend is consistent across all rock types. On the other hand, in the CAI-EQC relationship, when the EQC is zero, the CAI value can still exceed 1.2, indicating that CAI may remain high even in the absence of quartz content in some cases.

Zhang, Konietzky, et al. (2020) study factors affecting the CERCHAR abrasivity index with three rock types (granite, sandstone, and slate). They discover that the CAI value is not different between rough, sawn, and polished. They applied a stylus with a Rockwell hardness (HRC) of 54–56. Kotsombat, et al. (2020) explain that a lower scratching rate results in deeper grooves, a lower surface scraping force, and a lower CAI of the stylus pin. Thanadkha and Fuenkajorn, (2022) explain the difference between a smooth surface and a rough surface. On rough surfaces the CAI value is higher than on smooth surfaces.

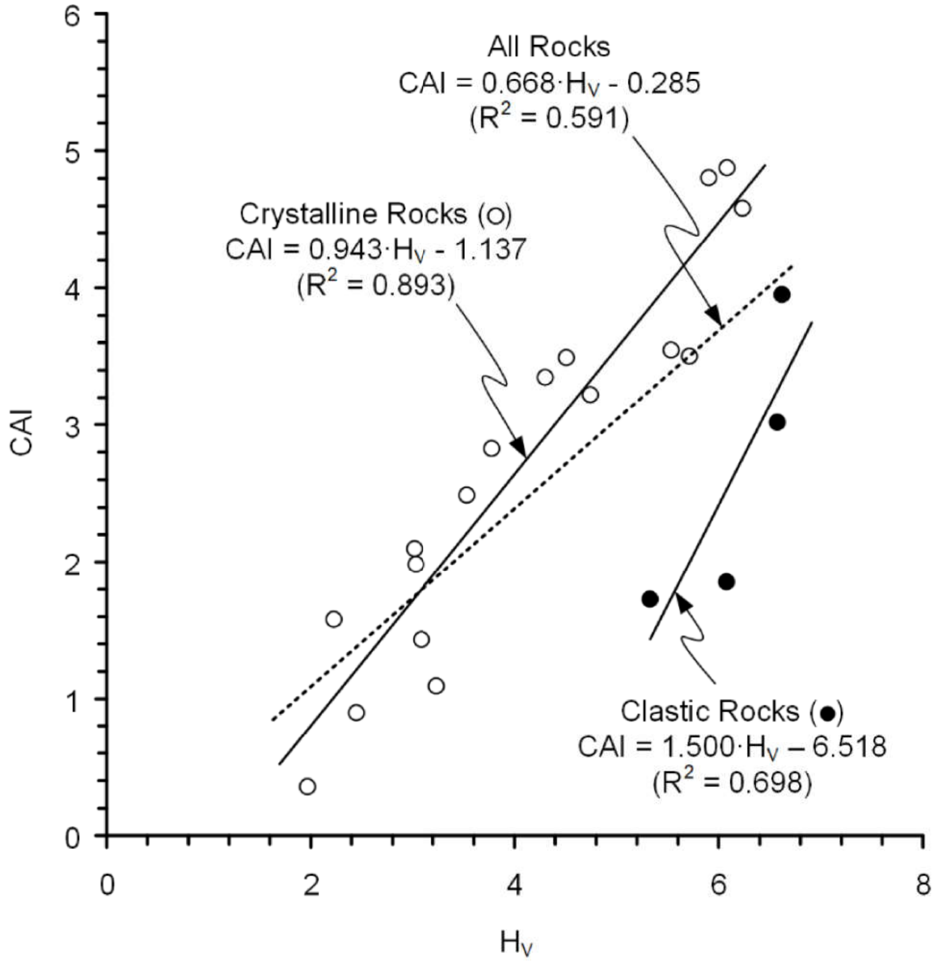


Figure 2.8 Correlation between CAI value and volumetric hardness (H_V) (Kathancharoen and Fuenkajorn, 2023).

2.3.2 Rock mechanical properties

Rock strength is significant factors affecting the value of CAI. Many researchers in this context consider several mechanical properties, including rock strength and rock hardness.

2.3.2.1 Strength of rock

Strength parameters such as uniaxial compressive strength, Brazilian tensile strength, and point load strength (IS) significantly influence the CAI values as proposed by Capik and Yilmaz, (2017). More researchers confirm this influence by identifying a strong linear relationship between CAI and both compressive strength and Brazilian tensile strength, as indicated by high coefficients of determination. Er and Tuğrul, (2016); Sirdesai, Aravind and Panchal, (2021).

Hamzaban, et al. (2014) study the new CERCHAR abrasivity testing device that determines friction force and penetration into rock surfaces. They discover a new parameter that explains the relationship between rock and stylus pin and the abrasiveness of rock. The CAI increases with the rise in uniaxial compressive strength, point load strength, Brazilian tensile strength, Schmidt rebound hardness, and the equivalent quartz content (EQC) (Capik and Yilmaz, 2017) (Figure 2.9). Alber, (2008) study CAI under stress. This indicates higher CAI values under confining pressure on the specimen within a triaxial test and demonstrates that the CAI is stress-dependent.

Deliormanli, (2012) study the relationship between strength and CAI value on soft rock using the methods of uniaxial compressive strength, direct share strength, Bohme abrasion, and wide wheel abrasion values. (Figures 2.10 and 2.11).

Kathancharoen and Fuenkajorn, (2023) explain that rock strength is significant factors affecting the value of CAI. Many researchers in this context consider several mechanical properties, including Young's modulus and Poisson's ratio. It indicates that both values affect the CAI of clastic rocks, but in crystalline rocks there is no effect on CAI. Therefore, it is predicted that in clastic rocks there may be some significant factors affecting the CAI value. The relationship between CAI and triaxial properties, particularly adhesion force and friction angle (Figures 2.12 and 2.13), in clastic rocks both values had an effect on CAI, whereas in crystalline rocks the effect on CAI was less, limiting the study's conclusions.

2.3.2.2 Hardness of rock

There are many methods to determine the hardness of rocks, such as Shore hardness, Schmidt hardness, Vickers hardness, and others. Many researchers find a relationship between CAI and Shore hardness, with R^2 values greater than 0.74 Er and Tuğrul, (2016); Lee, Jeong and Jeon, (2012); Ozdogan, Deliormanli and Yenice, (2018).

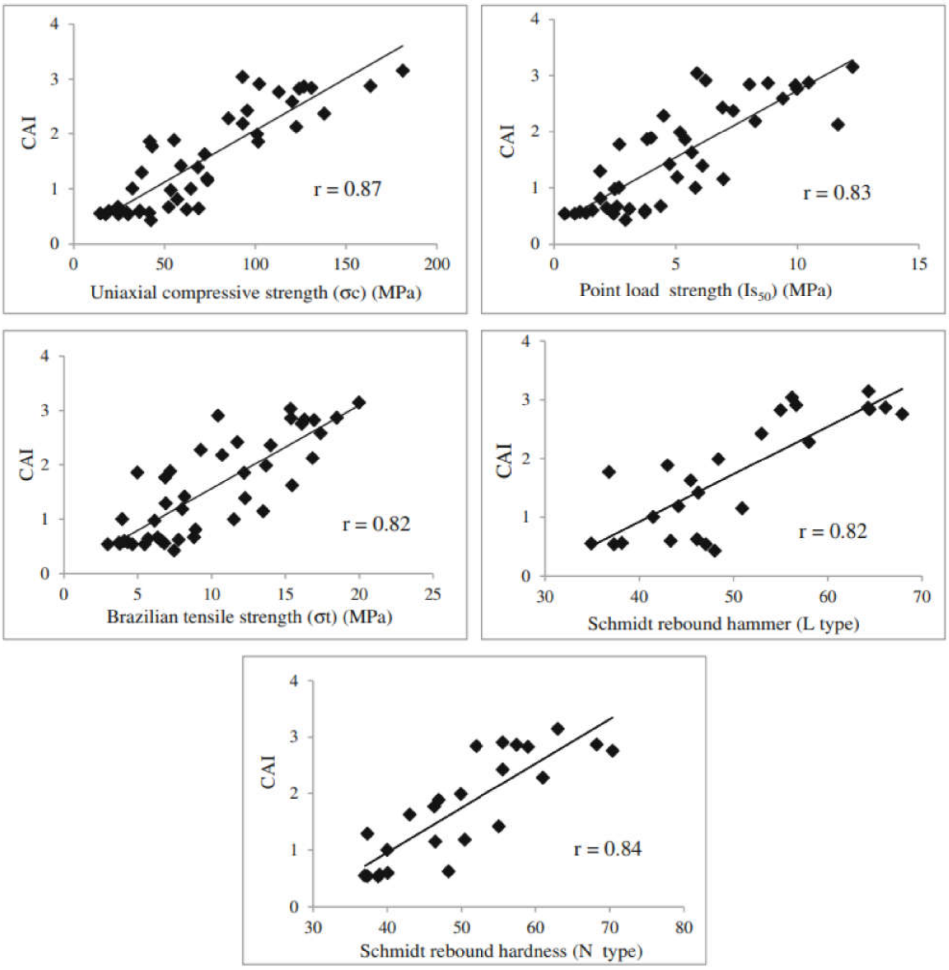


Figure 2.9 Relationships between CAI and mechanical properties of rock (Capik and Yilmaz, 2017).

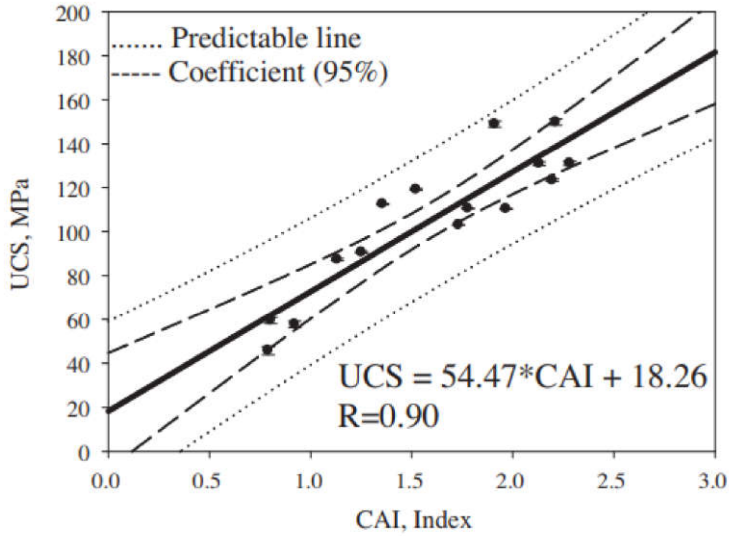


Figure 2.10 Scatter and relation graph of UCS versus CAI (Deliormanli, 2012).

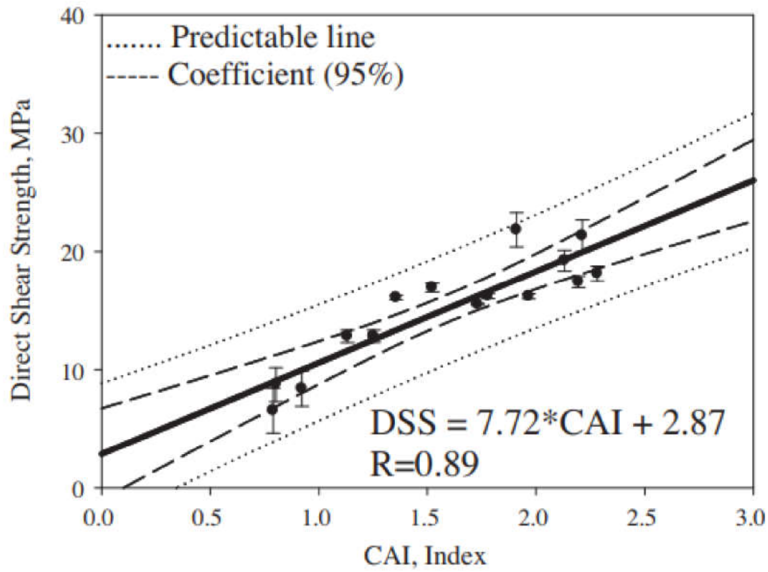


Figure 2.11 Scatter and relation graph of DSS versus CAI (Deliormanli, 2012).

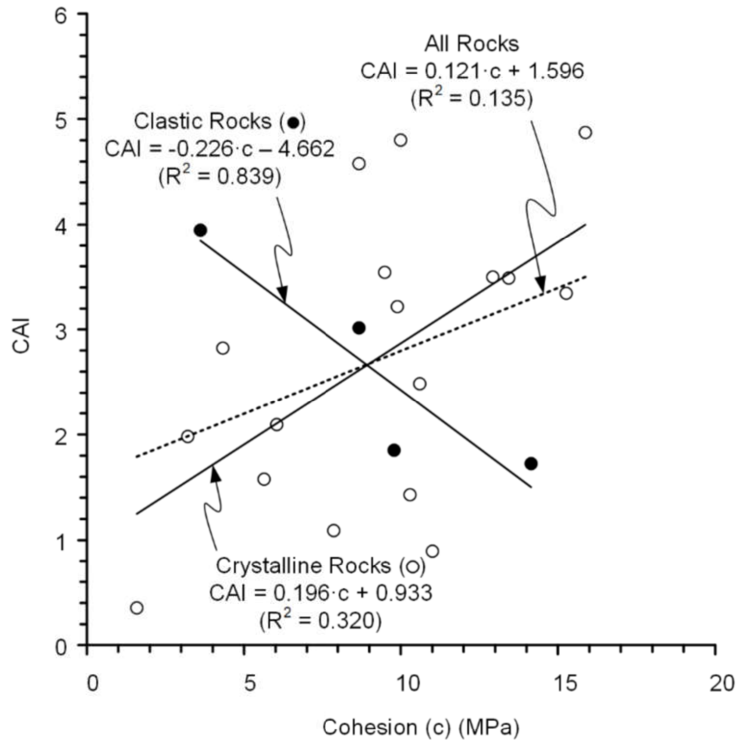


Figure 2.12 Correlation between CAI value and rock cohesion (c) (Kathancharoen and Fuenkajorn, 2023).

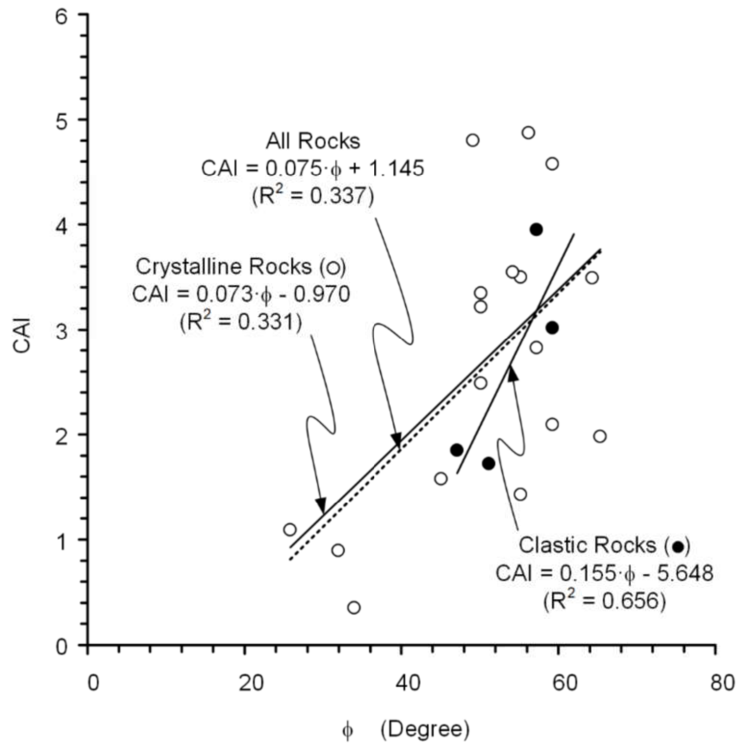


Figure 2.13 Correlation between CAI value and friction angle (ϕ) (Kathancharoen and Fuenkajorn, 2023).