CORRELATION BETWEEN CERCHAR ABRASIVITY INDEX OF SMOOTH AND ROUGH ROCK FRACTURES

PHRAWNAPHA THANADKHA

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Civil, Transportation and Geo-resources Engineering

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ความสัมพันธ์ระหว่างดัชนีความสึกกร่อนแบบเซอคาร์ของรอยแตกเรียบและรอยแตกขรุขระของหิน

นางสาวพราวนภา ถนัดค้า

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a Master's Degree.

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พราวนภา ถนัดค้า : ความสัมพันธ์ระหว่างดัชนีความสึกกร่อนแบบเซอคาร์ของรอยแตกเรียบและรอยแตกขรุขระของหิน (CORRELATION BETWEEN CERCHAR ABRASIVITY INDEX OF SMOOTH AND ROUGH ROCK FRACTURES) อาจารย์ที่ปรึกษา : ศาตราจารย์ (เกียรติคุณ) ดร.กิตติเทพ เฟื่องขจร, 50 หน้า.

คำสำคัญ: ความสึกกร่อน/ปริมาณแร่ควอตซ์สมมูล/กำลังอัดในแกนเดียว/รอยแตก

วัตถุประสงค์ของการศึกษานี้เพื่อหาความสัมพันธ์ของดัชนีความสึกกร่อนแบบเซอคาร์ (CAI) ระหว่างรอยแตกผิวเรียบ (CAI_s) และรอยแตกขรุขระ (CAI_r) นอกจากนี้กำลังอัดในแกนเดียวและปริมาณแร่ควอตซ์สมมูลได้มีการนำมาพิจารณาความสัมพันธ์กับ CAI มีการทดสอบตัวอย่างหินจำนวน 19 ชนิด ที่พบได้ทั่วไปในภาคเหนือและภาคตะวันออกเฉียงเหนือของประเทศไทย แบ่งออกเป็นห้ากลุ่ม ได้แก่ กลุ่มหินตะกอนอนุภาค, อัคนีแทรกซอน, คาร์บอเนต, ซัลเฟตและคลอไรด์ และภูเขาไฟ ตัวอย่างรอยแตกผิวเรียบได้มาจากการตัดด้วยเลื่อยและรอยแตกผิวขรุขระเตรียมจากแรงดึง จากผลการทดสอบที่ได้ ค่า CAI ของพื้นผิวขรุขระสูงกว่าพื้นผิวเรียบ 1.2 เท่า ได้ค่าสัมประสิทธิ์สหสัมพันธ์ (R^2) ของความสัมพันธ์ระหว่าง CAI_s และ CAI_r ที่ดี โดยมีค่ามากกว่า 0.9 ความสัมพันธ์ระหว่างกำลังอัดในแกนเดียวและดัชนีความสึกกร่อนทั้งจากพื้นผิวเรียบและขรุขระมีความสัมพันธ์ที่ค่อนข้างดี (R^2 > 0.7) โดย CAI_s แสดงสัมประสิทธิ์สหสัมพันธ์กับกำลังอัดในแกนเดียวได้ดีกว่า CAI_r เล็กน้อย สำหรับความสัมพันธ์ระหว่างดัชนีความสึกกร่อนแบบเซอคาร์และปริมาณแร่ควอตซ์สมมูลที่ได้รับค่อนข้างแย่ ซึ่งอาจมีสาเหตุมาจากความไม่หลากหลายของประเภทและคุณสมบัติของหินที่นำมาทดสอบ

สาขาวิชา เทคโนโลยีธรณี ลายมือชื่อนักศึกษา พราวนภา

ปีการศึกษา 2565 ลายมือชื่ออาจารย์ที่ปรึกษา K. Fuen

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Keyword: Abrasivity/Equivalent quartz content/Rock strength/Fractures

The objective of this study is to determine the correlation of CERCHAR abrasivity index (CAI) between smooth (CAI_s) and rough (CAI_r) fractures. Uniaxial compressive strength and equivalent quartz content are also correlated with CAI. Nineteen types of rock specimens commonly found in the north and northeast of Thailand are prepared to obtain saw-cut surfaces and tension-induced fractures. They are classified into five groups: clastic, plutonic, carbonate, sulfate and chloride, and volcanic groups. Results indicate that CAI values of rough surface is slightly higher than those of smooth surface with factor of 1.2. Good linear correlation is obtained as indicated by the coefficient of correlation (R^2) is greater than 0.9. Both abrasivity indexes obtained from rough and smooth surfaces correlate fairly well with the rock compressive strength (R^2 > 0.7). CAI_s shows slightly better correlation with the strength than CAI_r does. Correlation between CAI values and equivalent quartz content is relatively poor. This may be due to the fact that relatively narrow range of rock characteristics have been used in the test.

School of Geotechnology
Academic Year 2022

Student's Signature ....พราวนภา....
Advisor's Signature ....

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Phrawnapha Thanadkha

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF FIGURES (Continued)

Figure **Page**

SYMBOLS AND ABBREVIATIONS

EQC	=	Equivalent Quartz Content
CAI	=	CERCHAR abrasiveness index
CAI_s	=	CERCHAR abrasiveness index of smooth fracture
CAI_r	=	CERCHAR abrasiveness index of rough fracture
d	=	Scratching distance
H_M	=	Hardness of each mineral based on Mohs scale
HRC	=	Rockwell Hardness
N	=	Number of rock types
R_i	=	Rosiwal abrasiveness
W_i	=	Mineral amount
s_i	=	Mean misfit
$X_{j,p}$	=	Predicted CERCHAR abrasiveness index values of rough surfaces
$X_{j,t}$	=	Measured CERCHAR abrasiveness index values of rough surfaces
σ_c	=	Uniaxial compressive strength

CHAPTER I

INTRODUCTION

1.1 Background and Rationale

Rock abrasion is important in excavation processes. CERCHAR abrasiveness test has been widely used to assess rock abrasivity because it is simple and low cost (Ho et al., 2016). CERCHAR abrasiveness index (CAI) can be correlated with the wear of tools used in mining, drilling and tunnelling. The CAI values depend on many factors, such as surface conditions, pin hardness, pin speed, and properties of rock. Plinninger et al. (2003) and Käsling and Thuro (2010) conduct CERCHAR test to study the surface conditions. CAI values of the rough rock samples are higher than that of the smooth samples. They propose that CAI values of rough surfaces are 1.14 times of those of smooth surfaces. Such correlation also shows high variations or high standard of deviation (± 0.79). CAI increases with increasing uniaxial compressive strength (Teymen, 2020). Al-Ameen and Waller (1994) show poor correlation between the CAI and rock mineral contents. This agrees with the results obtained by Torrijo et al. (2019) who find that the relation between CAI and equivalent quartz content (EQC) is not clear.

Many studies have been carried out to assess the correlation between CERCHAR abrasiveness index of rough and smooth surfaces. Several investigators show coefficient of correlations (R^2) as 0.74 (Plinninger et al., 2003), 0.69 (Käsling and Thuro, 2010), 0.89 (Aydın et al., 2016), and 0.81 Yaralı and Duru (2016). These wide ranges of the multiplied factors deserve further investigation in particular on the factors controlling the CAI under different degrees of roughness of the tested surfaces.

Therefore, the multiplier factor was studied to apply the correlation between CAI of smooth and rough surfaces of rocks in Thailand.

1.2 Research Objectives

The objective of this study is to investigate the correlation of CAI between smooth and rough surfaces. A new mathematical relation is derived to obtain a better correlation coefficient. The multiplication factors for the correlation between the CAI of smooth and rough rock surfaces determined in other investigators are different. The main task involves performing CAI tests on smooth and rough rock surfaces in Thailand and developing a new multiplied factor for the results of smooth and rough surfaces testing. Nineteen rock types commonly found in the north and northeast of Thailand are selected in this study. These rocks are subjected to various tools of excavation. The relation between CAI and mineral compositions of the rocks is also investigated. X-ray diffraction analysis is performed to determine the mineral compositions of the rock specimens.

1.3 Scope and Limitations

The scope and limitations of the study are as follows:

1) Laboratory testing is performed on saw-cut and rough rock fractures of nineteen rock types in north and northeast of Thailand. These rocks are classified into five groups: clastic (Phu Phan, Sao Khua, Phra Wihan, and Phu Kradung sandstones), plutonic (granite, alaskite, and diorite), carbonate (marble, travatine, and limestone), sulfate and chloride (gypsum and rock salt), and volcanic groups (basalt, volcanic tuff, and andesite).

2) The CERCHAR test procedure follows ISRM suggested method for determining the abrasivity of rock by the CERCHAR abrasivity test.

3) The testing is performed under dry condition.

4) The wear flat of stylus tip before and after the CERCHAR testing is measured under microscope.

5) Each stylus tip is measured around its axis in 0°, 90°, 180°, and 270° directions.

1.4 Research Methodology

The research methodology shown in Figure 1.1 comprises 6 steps: including literature review, samples collection and preparation, CERCHAR testing, analysis of test results, discussions and conclusions, and thesis writing.

1.4.1 Literature review

Literature reviews are performed to study the researches inducing rock abrasiveness, CERCHAR testing, factor affecting CERCHAR abrasiveness index, and correlation between CERCHAR abrasivity index and rock properties.

1.4.2 Samples preparation

Nineteen types of rock specimens used in this study are prepared to obtained smooth and rough fractures. These rocks are classified into five groups: clastic, plutonic, carbonate, sulfate and chloride, and volcanic groups. They are commonly found in north and northeast of Thailand. The smooth surfaces are prepared by saw-cutting. The rough surfaces are produced by tension-inducing method using line loading. X-ray diffraction analysis (XRD) is performed to determine the mineral compositions of the rock samples.

1.4.3 CERCHAR testing

The CERCHAR testing has been performed on smooth and rough surfaces under dry condition using a device based on West apparatus (West, 1989), as shown in Figure 1.2. The apparatus comprises vice holding rock sample, a pin chuck or casing for the stylus, a static load of 70 N, and a hand crank. The rock specimen is moved underneath the stylus. The stylus has Rockwell hardness (HRC) of 55 ± 1. The test procedure follows the ISRM suggested method (Alber et al., 2014) for determining the abrasivity of rock by the CERCHAR Abrasivity. The scratching length of rock specimens is 10 mm. Test duration is 10 s, resulting in a scratching rate of 1 mm/s. The wear flat of stylus tip before and after the CERCHAR testing is measured under microscope. Each stylus tip is measured around its axis in 0°, 90°, 180°, and 270° directions.

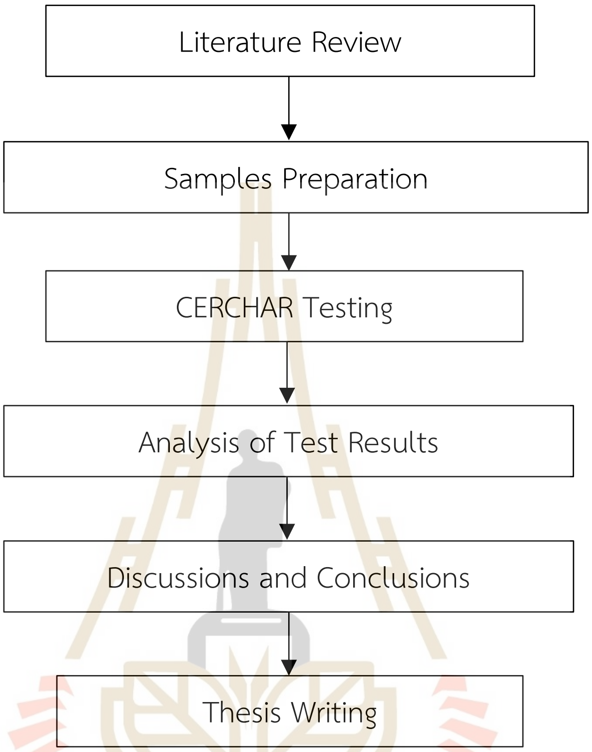

Figure 1.1 Research methodology.

Figure 1.2 Test apparatus used in this study based on West apparatus (West, 1989).

1.4.4 Analysis of test results

The pin wear after CERCHAR testing is measured to predict the CAI values of smooth and rough surfaces by using microscope. The results are analyzed to study the correlations of CERCHAR abrasivity index between smooth (CAI_s) and rough (CAI_r) surfaces. Uniaxial compressive strength (σ_c) and equivalent quartz content (EQC) are also correlated with CAI. The mean misfit (s_i) is determined for each correlation between CAI_r and CAI_s.

1.4.5 Discussions and conclusions

Discussions describe the reliability and adequacy of test information. Comparisons of results and explanations of the problem are described and offered here. Future research needs are identified.

1.4.6 Thesis writing

All research activities, methods, and results will be documented and complied in the thesis. This study can be applied to reduce maintenance costs and prediction of abrasivity/wear resistance of devices, such as chisel bit, drill bit and disc cutter, etc. The findings are published in the conference proceedings.

1.5 Research Methodology

Chapter I describes the background of problems and significance of the study. The research objectives, methodology, scope and limitations and identified. Chapter II summarizes the results of the literature review. Chapter III describes the samples preparation. Chapter IV describes the laboratory tests method and prefer the test results. Chapter V describes the analyzed of the result. Chapter VI discusses and concludes the research results and provides recommendations for future research studies.

CHAPTER II
LITERATURE REVIEWS

2.1 Introduction

This chapter describes results of literature review performed to improve an understanding of rock abrasiveness, CERCHAR testing, factors affecting CERCHAR abrasiveness index, and correlation between CERCHAR index and rock properties.

2.2 Rock Abrasiveness

There are three methods commonly used for evaluating rock abrasivity in the laboratory: NTNU abrasion test, LCPC abrasivity test, and CERCHAR test. Only CERCHAR test does not require crushing of rock samples, and in terms of testing and functionality it is easier to perform than other tests. The test is a popular test to assess rock abrasivity (Ho et al., 2016). For the determination of rock abrasivity utilizing CERCHAR test, CERCHAR abrasivity index (CAI) has been used in an evaluation for abrasiveness of cutting and excavating tools. The CAI values have measured from tip wear of the steel stylus with a Rockwell Hardness between 54-56 HRC (Majeed and Bakar, 2019).

The NTNU/SINTEF test composes of a set of drill-ability tests. Three various sets include the drilling rate index (DRI), bit wear index (BWI) and cutter life index (CLI). These indexes are indirect measurements for rock drilling (Bruland, 2000). The above parameters for the NTNU/SINTEF test can be used to assess rock abrasivity, depending on the test objectives (Majeed and Bakar, 2019).

To decide rock abrasiveness from the LCPC abrasivity test, it is possible to determine the weight of carbon steel (grade XC 12) with a Rockwell hardness between 60-75 HRB, and then calculate the ABR or LCPC abrasivity index to determine the rock abrasiveness (Majeed and Bakar, 2019).

2.3 Factors Affecting CERCHAR Abrasiveness Index

2.3.1 Surface conditions

Al-Ameen and Waller (1994) study the CERCHAR test on soft sandstone, siltstone, silty mudstone, mudstone, seateart, ironstone, limestone, and igneous rocks in the UK. The CERCHAR test is performed on natural and polished rock specimens. The result shows coefficient of correlation (R^2) as 0.93, with strong linear correlation between CERCHAR abrasiveness index (CAI) of natural and polished rock surfaces. The relationship between the CAI values from the natural and polished rock specimens was obtained as follows:

$$CAI_{(natural)} = -0.01 + 1.00\ CAI_{(polish)} \tag{2.1}$$

Plinninger et al. (2003) conduct the CERCHAR test to study the surface conditions of inhomogeneous rock specimens. The CAI values of both smooth and rough rock samples are compared. Rough specimens are prepared by hammer forging and smooth specimens and prepared by water-cooled diamond saw cutting. The results show that the CAI values of the rough rock samples are approximately 0.5 times higher than the smooth samples. Figure 2.1 shows a trend that is good and appropriate. The coefficient of correlation (R^2) equal to 0.74. However, for non-homogeneous and anisotropic rock specimens wear hammering may result in an inappropriate surface after the fracture. The author recommends using a diamond saw for surface cutting. The relationship between the CAI values and the smooth and rough rock samples was obtained as follows:

$$CAI = 0.99\ CAI_s + 0.48 \tag{2.2}$$

where CAI is CERCHAR abrasiveness index of surface roughness and CAI_S is CERCHAR abrasiveness index of smooth surface cut by diamond saw.

Käsling and Thuro (2010) have collected information on rock laboratory test results from worldwide showing the pins hardness of Rockwell hardness HRC54-56, the CERCHAR test on smooth, saw-cut and rough rock specimens. From the data

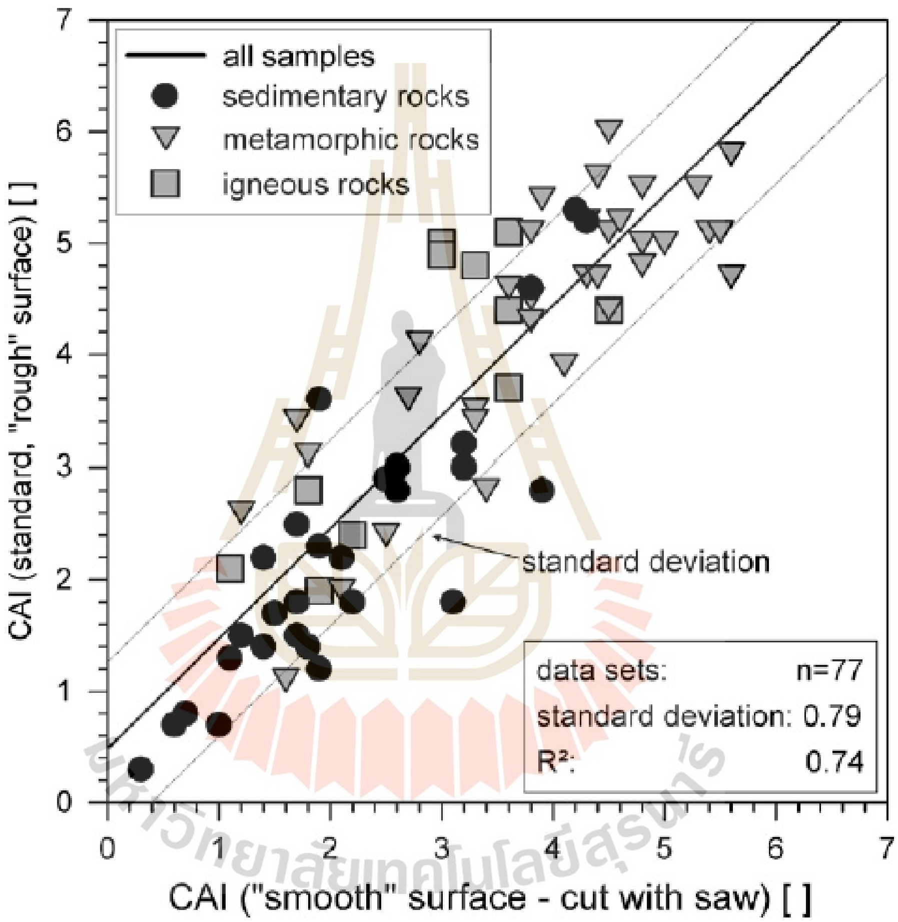

Figure 2.1 Relationship between CAI of rough and saw-cut surface (Plinninger et al., 2003).

collected, the CAI values of smooth surface is lower than that of rough surface (as shown in Figure 2.2). The coefficient of correlation (R^2) equals to 0.69. It was analyzed that for a high CAI, there was a high deviation, and the linear relationship between the CAI values of smooth and rough surfaces were obtained as follows:

$$CAI_{(smooth\ surface)} = 0.878\ CAI_{(rough\ surface)} \quad (2.3)$$

$$CAI_{(rough\ surface)} = 1.14\ CAI_{(smooth\ surface)} \quad (2.4)$$

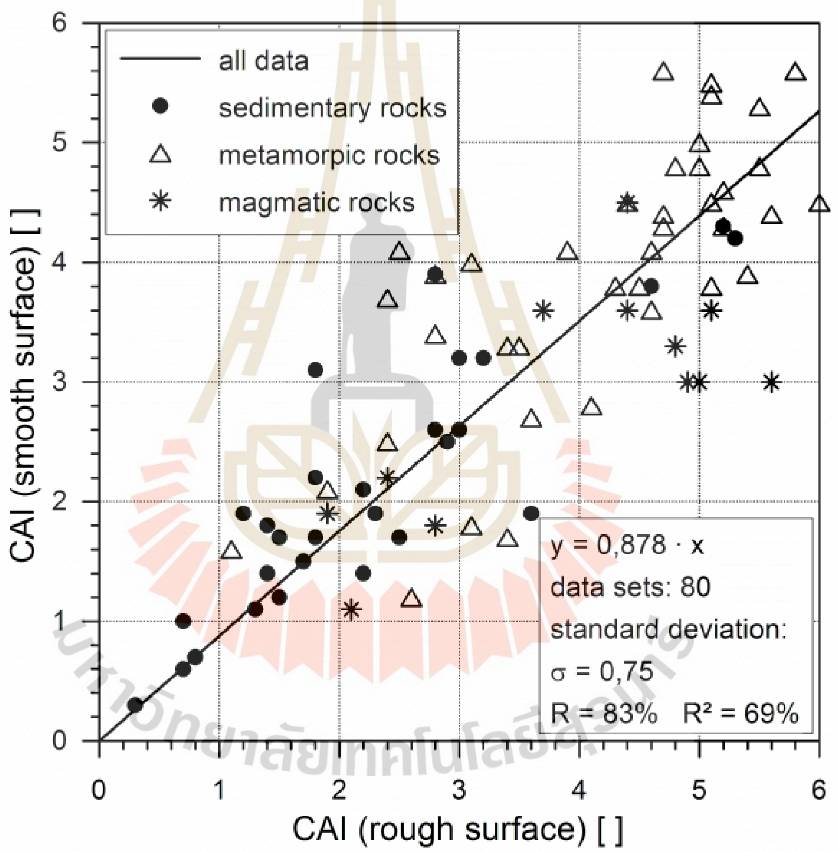

Figure 2.2 Relationship between CAI of rough and smooth, saw-cut surface in Käsling and Thuro (2010).

Yaralı and Duru (2016) perform CERCHAR test to study the effects of saw-cut and roughness surface. A total of 15 rock samples were tested. CAI was determined using ASTM D7625-10. It was found that the CAI of roughness (CAI_r) was 18% higher than that of saw-cut surface (CAI_s) (Figure 2.3). The correlation coefficient (R^2) is 0.81. The linear relationship between CAI_r and CAI_s was obtained as follows:

$$CAI_r = 1.1683\ CAI_s - 0.2186 \qquad (2.5)$$

where CAI_r is CERCHAR abrasiveness index of rough surfaces and CAI_S is CERCHAR abrasiveness index of saw-cut surface. Aydın et al. (2016) investigate the effects of factors on CAI by performing with two different test apparatus both on rough and saw-cut specimen surfaces. The result show that rough surface CAI (CAI_r) values are generally greater than the saw-cut surface CAI (CAI_s) by about 15%. The correlation coefficient is 0.89 and the correlation between CAI_r and CAI_s was obtained as follows:

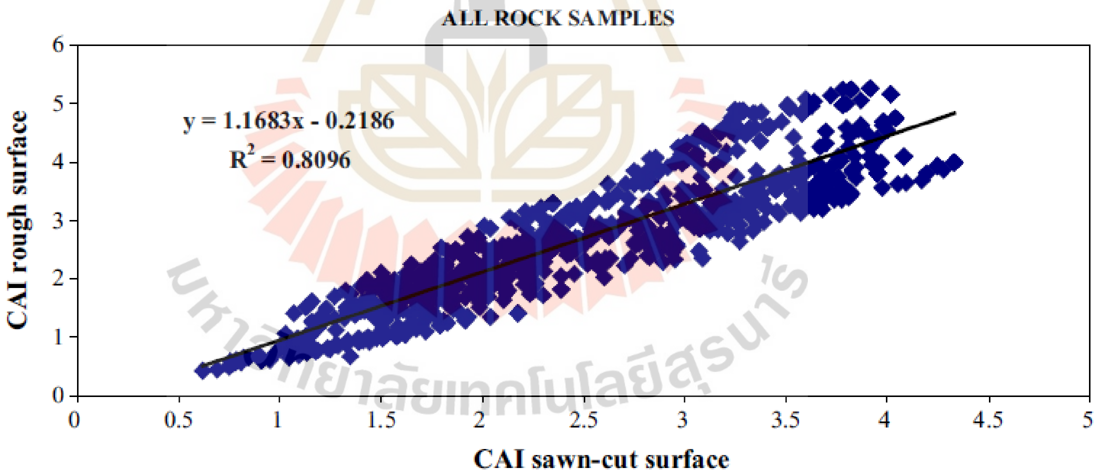

Figure 2.3 Relationship between CAI of rough surface and saw-cut surface (Yaralı and Duru, 2016).

$$CAI_r = 1.141\ CAI_s - 0.203 \quad (2.6)$$

where CAI_r is CERCHAR abrasiveness index of rough surfaces and CAI_S is CERCHAR abrasiveness index of saw-cut surface. Surface condition has affected on the CAI values which CAI of rough surface mainly higher than that of saw-cut surface (Aydın, 2019) (Figure 2.4). The coefficient of correlation between CAI_r and CAI_s equal to 0.96. The linear relationship between CAI_r and CAI_s was obtained as follows:

$$CAI_r = 1.119\ CAI_s \quad (2.7)$$

where CAI_r is CERCHAR abrasiveness index of rough surfaces and CAI_S is CERCHAR abrasiveness index of saw-cut surface. Zhang et al. (2020) study surface conditions affecting the CAI on rough, sawn, and polished. The tests are performed on granite, sandstone, and slate. Results show that the CAI values of rough surfaces are higher than those sawn surfaces and higher than those polished surfaces.

2.3.2 Pin hardness

Jacobs and Hagan (2009) study the effect of stylus hardness (HRC 15, 24, 29, 35, 40, 45, 50, 55 and 60) on CAI for sandstone, granite, hematite, coal and shale, which have different physical and mechanical properties. It is founded that CAI decreases linearly with steel hardness. The rate of reduction in CAI was independent of rock type. The results agree well with those of Rostami et al. (2014) who study the effect of pin hardness on the CERCHAR test from CAI values using different pin hardness. Seven types of rock specimens were tested (including slate, limestone, sandstone, quartzite, calcite, granite, and marble) with both saw-cut and rough samples. The CAI values of the pin HRC 41/43 are higher than the CAI value of the pin HRC 54/56 for both saw-cut and rough samples.

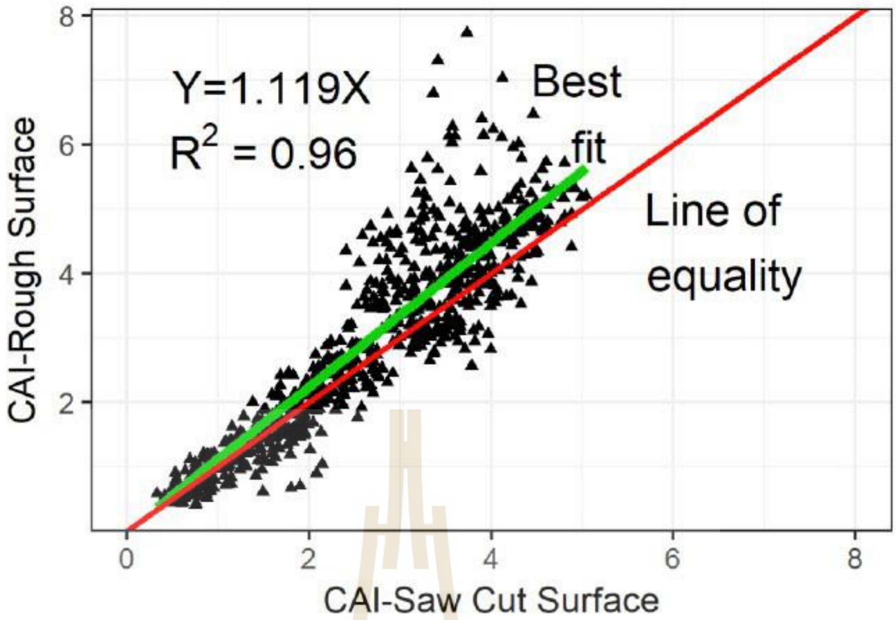

Figure 2.4 Correlation between CAI-Rough surface and CAI-Saw cut surface (Aydın, 2019).

2.3.3 Method for measuring stylus tip

The effect of the stylus tip measurement method has significantly affected on the CAI. For test of rough rock specimens, wear flat hard rocks are amorphous with stylus burrs (Figure 2.5). For stylus tip measurements, side view measurements are recommended because top view measurements have never been visible to burrs extending from the stylus tip, which affects the CAI value greatly (Rostami et al., 2014).

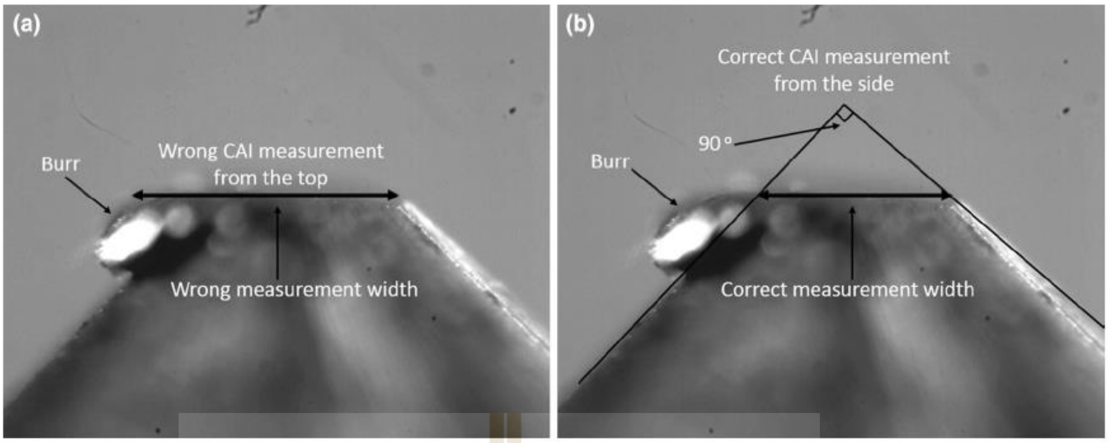

Figure 2.5 View of pin tip wear surface measured from the top view (a) and the side view (b) (Rostami et al., 2014).

2.4 Correlation between CERCHAR and rock properties

2.4.1 Physical properties

Alber (2008) investigates the relationship between CAI and porosity by testing four rock samples: sandstone, greywack, granite and mica-schist, with porosity (%) were 22.6, 9.7, 4.33, and 0.53, respectively. The CAI and porosity correlation shows that stones with higher porosity increased abrasivity and increased CAI, as shown in Figure 2.6 but Ozdogan et al. (2018) analyze the relationship between CAI and porosity by testing rock samples of marble, limestone, basalt, and granite. The tests reveal that the relationship between CAI and porosity are non-linear.

Hardness of rock affects the CAI value, which involves the hardness of minerals, grain size, texture, compaction of rock, etc. The relationship between CAI and hardness is that the CAI value increases as the hardness increases (Er and Tuğrul, 2016). Zhang et al. (2021) investigate relationship between CAI and mineral hardness of limestone and granite. The results indicate that hardness of granite is higher than that of limestone and the CAI increased with increasing mineral hardness.

2.4.2 Mechanical properties

Deliormanlı (2012) studies the relationship between CAI and the strength of marble stone by assessing and analyzing the test results using a regression analysis method, where strength was obtained from uniaxial compressive and direct shear tests. The test assessed whether CAI was significant on rock strength. Coefficient of correlation equals to 0.90 for uniaxial compressive strength (σ_c) and equals to 0.89 for direct shear strength. CAI increased when increasing rock strengths, as shown in Figures 2.7 and 2.8. This agrees with Er and Tuğrul (2016) who find that the linearly relation between CAI and σ_c. Teymen (2020) tests CERCHAR on 80 rock samples (including igneous, sedimentary, and metamorphic rocks) and analyzed the correlation between CAI and σ_c. The correlation between CAI and σ_c was linear, with CAI increases when increasing σ_c. He et al. (2016) investigate the correlation between CAI and σ_c of

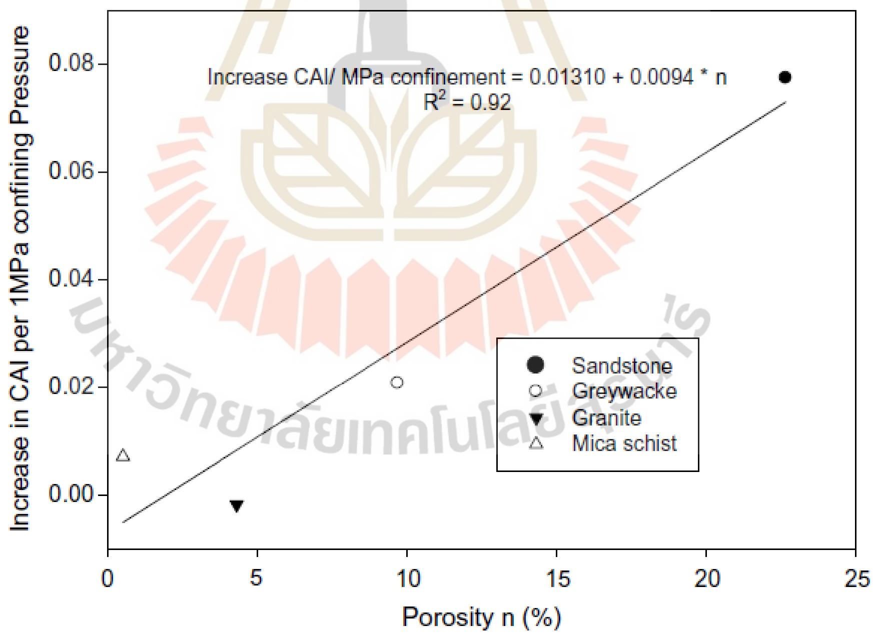

Figure 2.6 Relationship between CAI per a confining pressure (MPa) and porosity (Alber, 2008).

sandstone, mudstone, marble, tuff, diorite, and granite. The results indicate that of σ_c show linear correlation with CAI and the coefficient correlation R2 equals to 0.43. Ko et al. (2016) study the effect of mechanical properties on CAI. The tests are performed on granite, pegmatite, propylite, diorite, gabbro, gneiss, and schist. The results show linear relation between CAI and σ_c. The correlation coefficients (R^2) are 0.239 and 0.484 for igneous and metamorphic rock, respectively.

Capik and Yilmaz (2017) investigate the relationship between CAI values and σ_c by testing a total of 25 rock specimens, a total of 43 rock specimens from different areas. It was found that CAI increased with increasing σ_c with correlation coefficient of 0.87, as shown in Figure 2.9. In addition, the correlation among CAI and

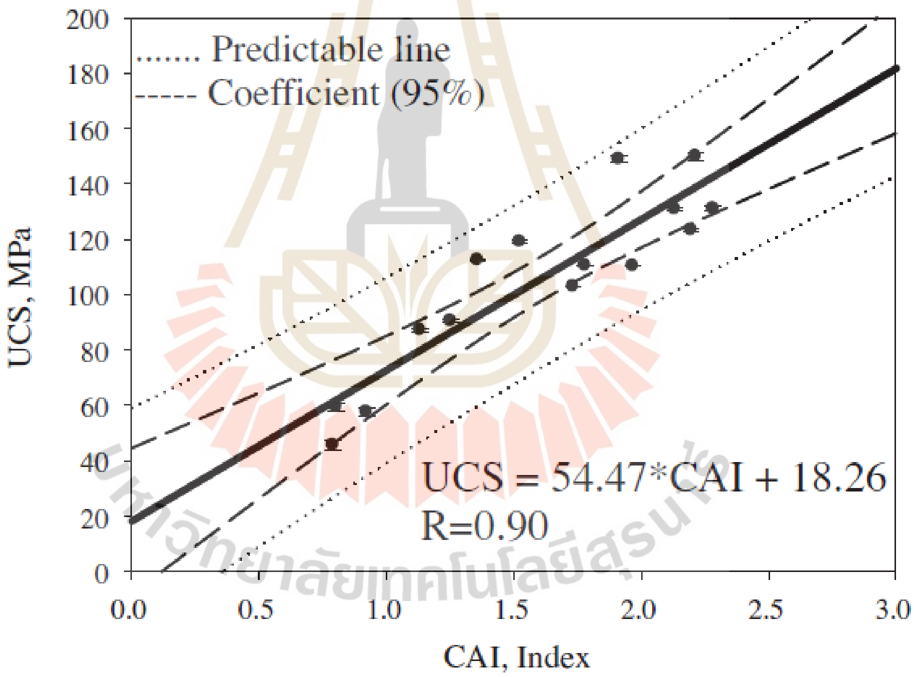

Figure 2.7 Relationship between CAI and uniaxial compressive strength (Deliormanlı, 2012).

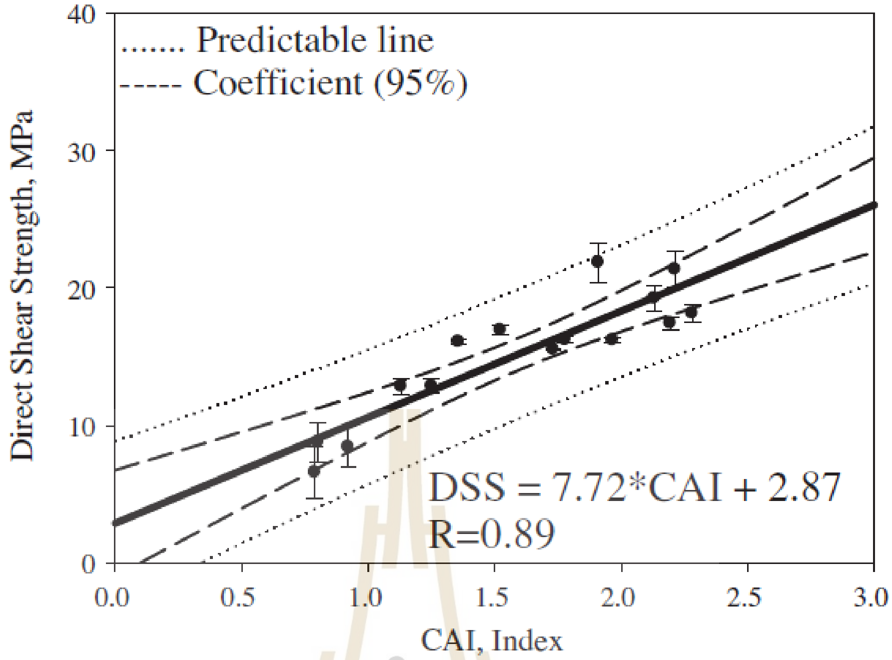

Figure 2.8 Relationship between CAI and direct shear strength (Deliormanlı, 2012).

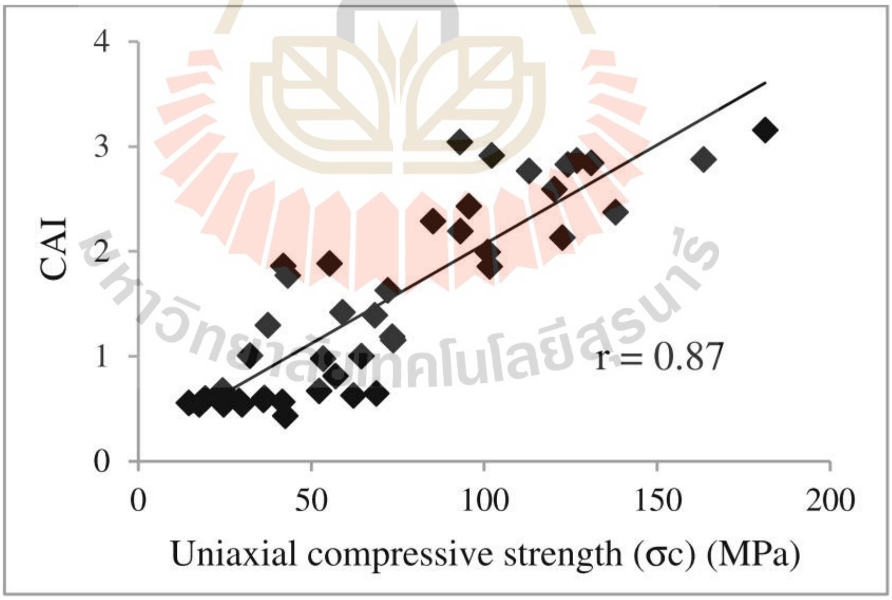

Figure 2.9 Relationship between CAI and uniaxial compressive strength (Capik and Yilmaz, 2017).

point load strength and brazilian tensile strength were also assessed. The CAI increases with increasing point load strength and Brazilian tensile strength. Whereas, Ozdogan et al. (2018) investigate the correlation between the CAI and mechanical properties of marble, basalt, granite, and limestone. The authors founded that the uniaxial compressive strength of rocks was poor correlation with CAI (R^2 = 0.151).

2.4.3 Mineral compositions

Equivalent quartz content (EQC) is one of the most commonly used parameters to correlate CAI with the mineral compositions of rock. This is mainly due to the fact that quartz is hard and abrasive mineral. Equivalent quartz content (EQC) of rock samples can be calculated as proposed by Thuro (1997):

$$EQC = \sum_{i=1}^{n} W_i \times R_i \tag{2.8}$$

$$R_i = \exp\left[(H_M - 2.12)/1.05\right] \tag{2.9}$$

where EQC is equivalent quartz content (%), W_i is mineral amount (%), n is number of minerals, R_i is Rosiwal abrasiveness (%) (Thuro, 1997), H_M is hardness of each mineral based on Mohs scale (Dana, 1912; Hurlbut and Klein, 1977), and 2.12 and 1.05 are constant values from Thuro (1997). This approach presumes that tool wear is predominantly a result of the mineral content harder than steel (Mohs hardness of 5.5), especially quartz (Mohs hardness of 7). To include all minerals of a rock sample, the equivalent quartz content has been determined, meaning the entire mineral contents referring to the abrasiveness or hardness of quartz. Therefore, each mineral amount is multiplied with its relative Rosiwal abrasiveness to quartz (with quartz being 100%; Rosiwal, 1896, 1916).

Moradizadeh et al. (2016) determine the relationship between CAI and EQC values. Three types of rock samples were tested (including metamorphic 8 samples, igneous 10 samples and sedimentary rock 18 samples). The results showed that the relationship between CAI and EQC have been linear and the CAI value increases with increasing EQC, as shown in Figure 2.10. CAI increases with the increasing of EQC (Capik and Yilmaz, 2017). He et al. (2016) find that the correlation of EQC can be fitted by logarithmic relation.

On the contrary, no relationship was founded between CAI and other minerals (Er and Tuğrul, 2016). Similar correlations presented for the CAI and the abrasive mineral content by Al-Ameen and Waller (1994) could not be confirmed. This conclusion agrees with the findings by Torrijo et al. (2019) who conclude that the relation between CAI and EQC is not clear.

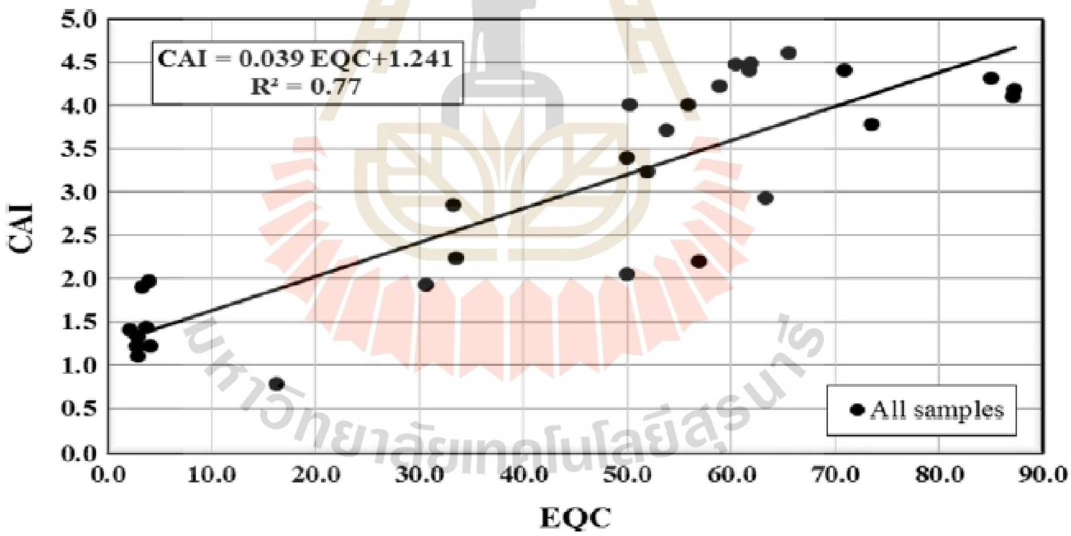

Figure 2.10 Correlation between CAI and equivalent quartz content (EQC) for all samples (Moradizadeh et al., 2016).

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

The objective of this chapter is to describe the sample preparation for CERCHAR testing on smooth and rough fractures under dry conditions and to determine mineral compositions by X-ray diffraction analysis (XRD).

3.2 Sample Preparation for CERCHAR Test

Nineteen types of rock specimens used in this study are prepared to obtained smooth and rough fractures. These rocks are classified into five groups: clastic, plutonic, carbonate, sulfate and chloride, and volcanic groups. They are commonly found in north and northeast of Thailand. Table 3.1 gives the rock units and types for each group. The smooth surfaces are prepared by saw-cutting. The rough surfaces are produced by tension-inducing method using line loading. The rock samples are prepared for CERCHAR testing, as shown in Figures 3.1 through 3.5.

3.3 X-ray diffraction analysis (XRD)

X-ray diffraction analysis (XRD) is performed to determine the mineral compositions of the rock samples. Samples of each rock type performed on crushed into fine power (with less than 2 μm in size) for XRD. The powder is then spread uniformly over the surface of a glass slid, using a small amount of adhesive binder. The instrument is constricted that this slide, when clamped in place, rotates in the path of collimated X-ray beam while a counting tube, mounted on an arm, rotates about is to take the reflected X-ray beam. The samples were analyzed at the Center of Scientific and Technological Equipment, Suranaree University of Technology. The mineral compositions are used as data basis to correlate with the mechanical properties and the wave velocities. Mineral compositions as obtained by XRD analysis are shown in Table 3.2.

Table 3.1 Rock units and types for each group.

Rock group	Rock Type	Code	Rock Unit	Location
Clastic	Sandstone	PPSS-1	Phu Phan Formation	Nakhon Ratchasima, Thailand
	Sandstone	PPSS-2	Phu Phan Formation	Nakhon Ratchasima, Thailand
	Sandstone	SKSS	Sao Khua Formation	Nakhon Ratchasima, Thailand
	Sandstone	PWSS	Phra Wihan Formation	Nakhon Ratchasima, Thailand
	Sandstone	PKSS	Phu Kradung Formation	Nakhon Ratchasima, Thailand
Plutonic	Granite	GN-1	Tak Batholith	Tak, Thailand
	Granite	GN-2	N/A	Phuket, Thailand
	Granite	GN-3	N/A	Ranong, Thailand
	Alaskite	AK	N/A	Nakhon Si Thammarat, Thailand
	Diorite	DR	Khao Phra Ngam Unit	Chonburi, Thailand

Table 3.1 Rock units and types for each group (Cont.).

Rock group	Rock Type	Code	Rock Unit	Location
Carbonate	Marble	MB	Khao Khad Formation	Lopburi, Thailand
	Travatine	TV	Khao Khad Formation	Saraburi, Thailand
	Limestone	LS	Khao Khad Formation	Saraburi, Thailand
Sulfate & Chloride	Gypsum	GS-1	N/A	Nakhon Sawan, Thailand
	Gypsum	GS-1	N/A	Nakhon Sawan, Thailand
	Gypsum	GS-2	N/A	Nakhon Si Thammarat, Thailand
	Rock salt	RS	Maha Sarakham Formation	Korat salt basin, Thailand
Volcanic	Basalt	BS	N/A	Buriram, Thailand
	Volcanic Tuff	VT	N/A	Saraburi, Thailand
	Andesite	AD	N/A	Saraburi, Thailand

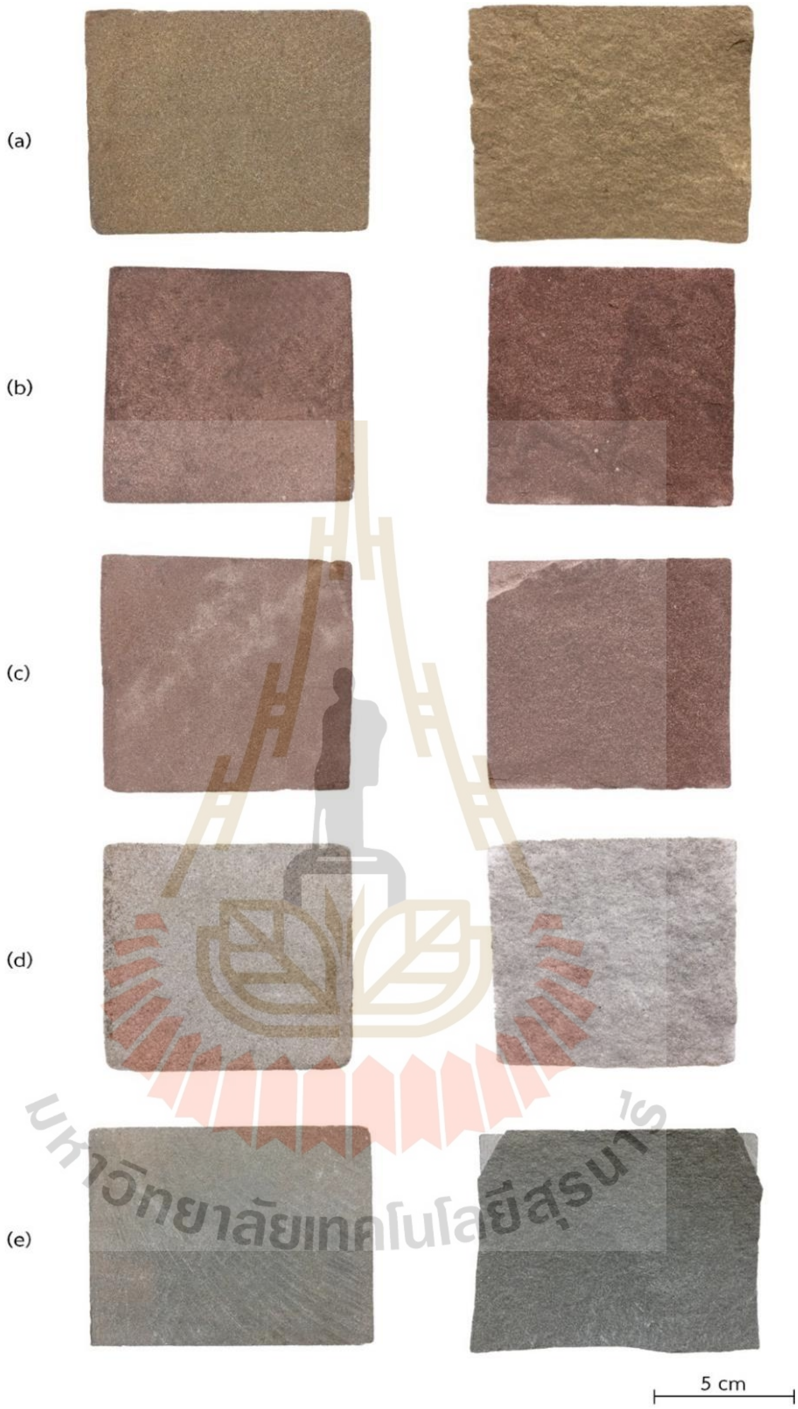

Figure 3.1 Rock samples used in CERCHAR test on smooth (left side) and rough (right side) surfaces in clastic group, Phu Phan sandstone (a), Phu Phan sandstone (b), Sau Khua sandstone (c), Phra Wihan sandstone (d), and Phu Kradung sandstone (e).

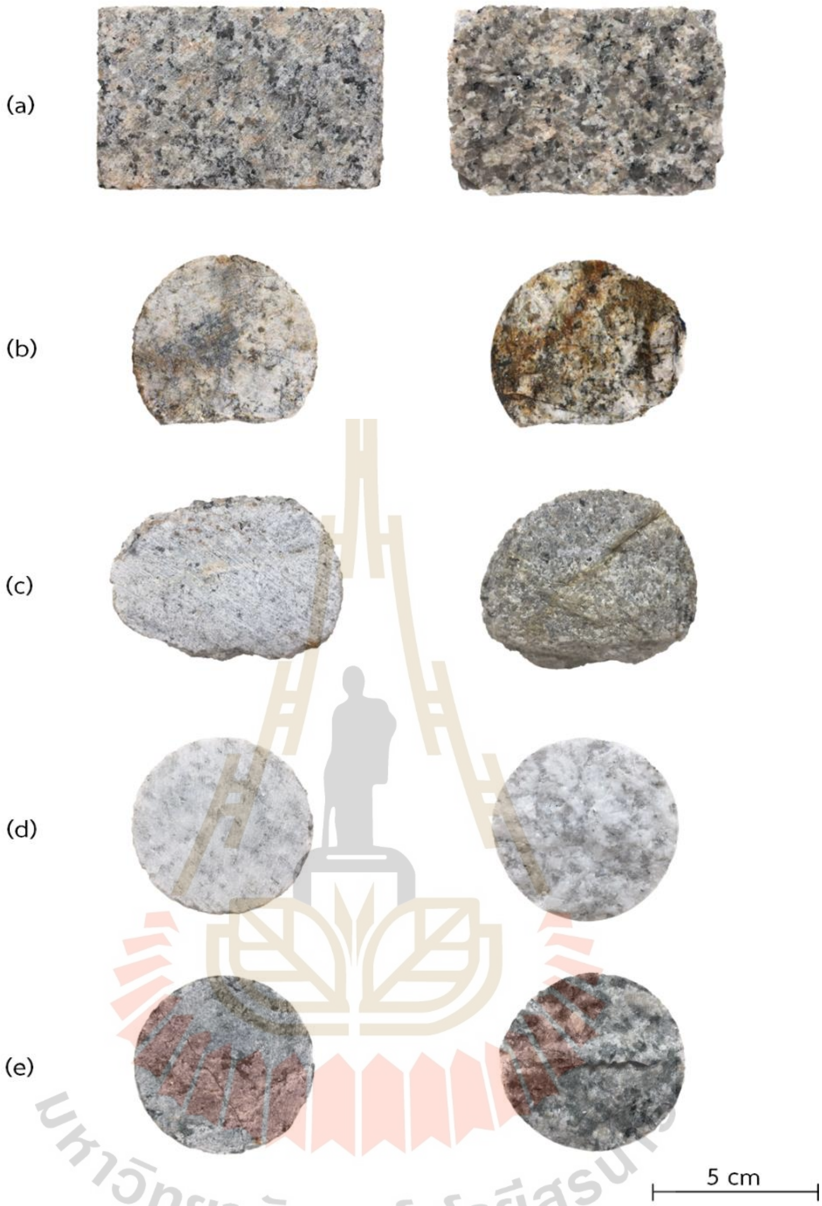

Figure 3.2 Rock samples used in CERCHAR test on smooth (left side) and rough (right side) surfaces in plutonic group, Tak granite (a), Phuket granite (b), Ranong granite (c), alaskite (d), and diorite (e).

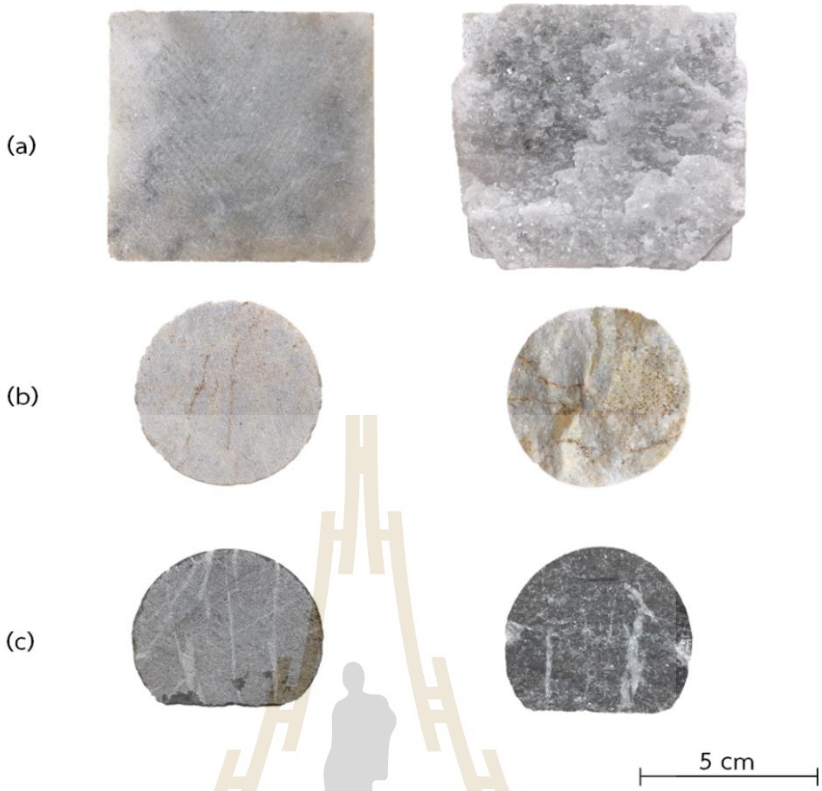

Figure 3.3 Rock samples used in CERCHAR test on smooth (left side) and rough (right side) surfaces in carbonate group, marble (a), travatine (b), and limestone (c).

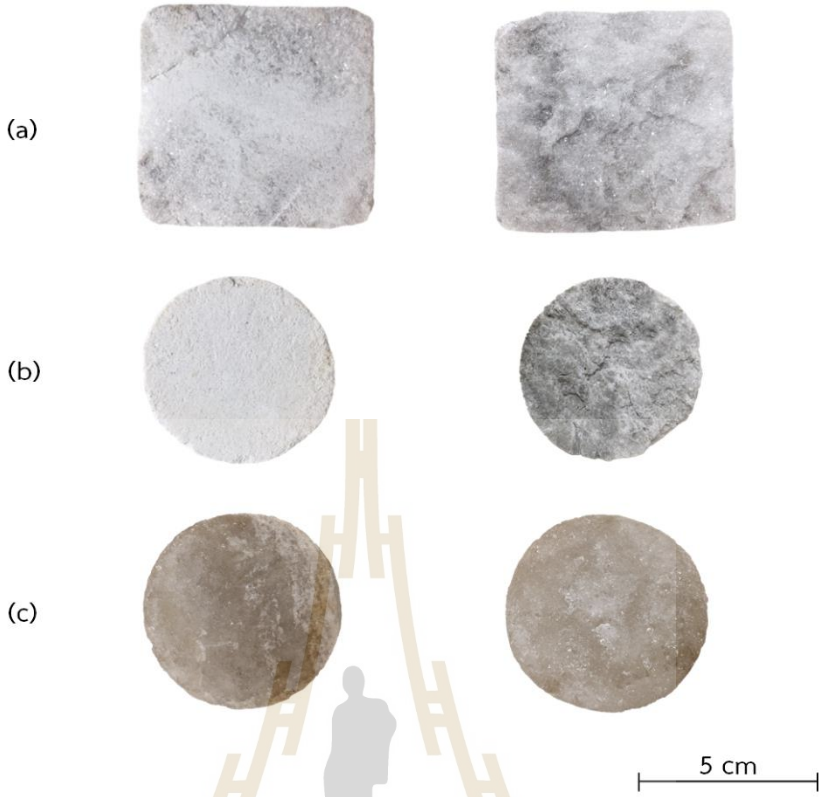

Figure 3.4 Rock samples used in CERCHAR test on smooth (left side) and rough (right side) surfaces in sulfate and chloride group, Suratthani gypsum (a), Nakhon Si Thammarat gypsum (b), and rock salt (c).

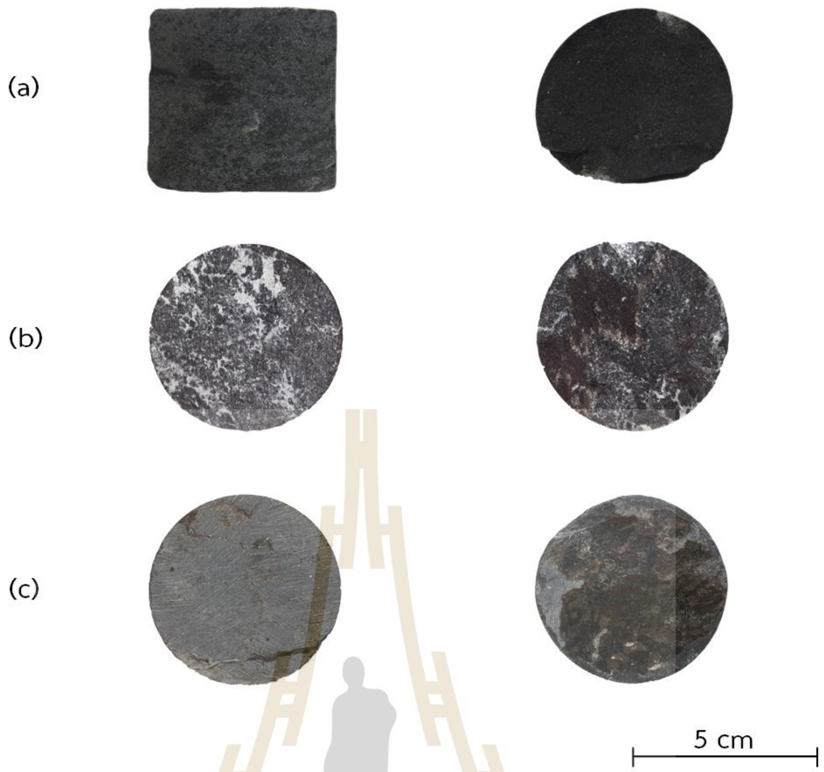

Figure 3.5 Rock samples used in CERCHAR test on smooth (left side) and rough (right side) surfaces in volcanic group, basalt (a), volcanic tuff (b), and andesite (c).

Table 3.2 Mineral compositions of all tested rocks obtained from X-ray diffraction analysis.

Rock group	Code	Mineral compositions
Clastic	PPSS-1	2.46% Feldspar, 6.29% Kaolinite, 91.26% Quartz
	PPSS-2	8.26% Albite, 2.00% Anorthite, 1.11% Calcite, 5.58% Chlorite, 0.25% Kaolinite, 3.35% Microcline, 0.25% Muscovite, 11.51% Oligoclase, 67.69% Quartz
	SKSS	5.55% Feldspar, 1.14% Hematite, 19.21% Muscovite, 74.10% Quartz
	PWSS	3.09% Feldspar, 5.73% Kaolinite, 7.90% Muscovite, 83.29% Quartz
	PKSS	28.95% Albite, 19.20% Chlorite, 11.15% Muscovite, 40.71% Quartz
Plutonic	GN-1	3.76% Amphibole, 22.67% Orthoclase, 44.90% Plagioclase, 28.67% Quartz
	GN-2	38.78% Albite, 5.15% Amphibole, 18.00% Anorthite, 4.37% Feldspar, 24.35% Microcline, 2.54% Plagioclase, 6.81% Quartz
	GN-3	28.62% Albite, 10.23% Anorthite, 0.86% Chlorite, 5.01% Diopside, 14.50% Muscovite, 13.75% Orthoclase, 27.04% Quartz
	AK	25.27% Albite, 11.49% Anorthite, 3.03% Chlorite, 3.22% Microcline, 0.78% Muscovite, 1.49% Orthoclase, 20.88% Plagioclase, 33.84% Quartz
	DR	22.59% Albite, 3.66% Anorthite, 3.66% Chlorite, 3.69% Diopside, 6.30% Muscovite, 15.30% Orthoclase, 44.82% Quartz

Table 3.2 Mineral compositions of all tested rocks obtained from X-ray diffraction analysis (Cont.).

Rock group	Code	Mineral compositions
Carbonate	MB	99.47% Calcite, 0.19% Feldspar, 0.35% Quartz
	TV	93.48% Calcite, 0.46% Chalcopyrite, 6.02% Dolomite, 0.05% Quartz
	LS	0.71% Actinolite, 92.24% Calcite, 5.05% Dolomite, 0.22% Fluorite, 1.79% Microcline
Sulfate & Chloride	GS-1	8.49% Calcite, 4.01% Chlorite, 87.50% Gypsum
	GS-2	2.66% Calcite, 8.75% Chlorite, 86.02% Gypsum, 2.57% Quartz
	RS	0.28% Anhydrite, 0.16% Dickite, 1.83% Gypsum, 95.50% Halite, 0.31% Sylvite
Volcanic	BS	19.45% Albite, 18.68% Anorthite, 3.89% Chlorite, 31.70% Diopside, 16.14% Microcline, 9.46% Muscovite, 0.69% Quartz
	VT	16.73% Albite, 2.60% Anorthite, 8.66% Calcite, 34.42% Chlorite, 5.57% Hematite, 22.49% Muscovite, 1.97% Orthoclase, 7.57% Quartz
	AD	2.91% Albite, 0.46% Anorthite, 4.28% Chlorite, 43.50% Kaolinite, 4.48% Muscovite, 0.80% Orthoclase, 43.59% Quartz

CHAPTER IV

LABORATORY TEST METHOD AND RESULTS

4.1 Introduction

This chapter describes test apparatus and method for determining the CERCHAR abrasivity index (CAI) of smooth and rough surfaces. The equivalent quartz content (EQC) calculation is also explained here. The results are used to investigate the correlation of abrasivity between smooth (CAI_s) and rough (CAI_r) surfaces. Uniaxial compressive strength (σ_c) and equivalent quartz content (EQC) are also correlated with CAI.

4.2 CERCHAR Testing

The CERCHAR testing is performed on smooth and rough fractures of rock specimens under dry condition using a device based on West apparatus (West, 1989), as shown in Figure 4.1.

4.2.1 Test apparatus and test method

The apparatus comprises vice holding rock sample, a pin chuck or casing for the stylus, a static load of 70 N, and a hand crank. The rock specimen is moved underneath the stylus. The stylus has Rockwell hardness (HRC) of 55 ± 1. The test procedure follows the ISRM suggested method (Alber et al., 2014) for determining the abrasivity of rock by the CERCHAR Abrasivity. The scratching length of rock specimens is 10 mm. Test duration is 10 s, resulting in a scratching rate of 1 mm/s. The wear flat of stylus tip before and after the CERCHAR testing is measured under microscope. Each stylus tip is measured around its axis in 0°, 90°, 180°, and 270° directions, as shown in Figure 4.2. The measured results are averaged.

The CERCHAR abrasiveness index values of smooth and rough surfaces can be calculated as follows:

$$CAI_r \text{ or } CAI_s = d \tag{4.1}$$

where CAI_r or CAI_s is CERCHAR abrasiveness indexes of rough and smooth surfaces, respectively, d is diameter of scratch flat area of stylus tip measured to the nearest of 0.001 mm.

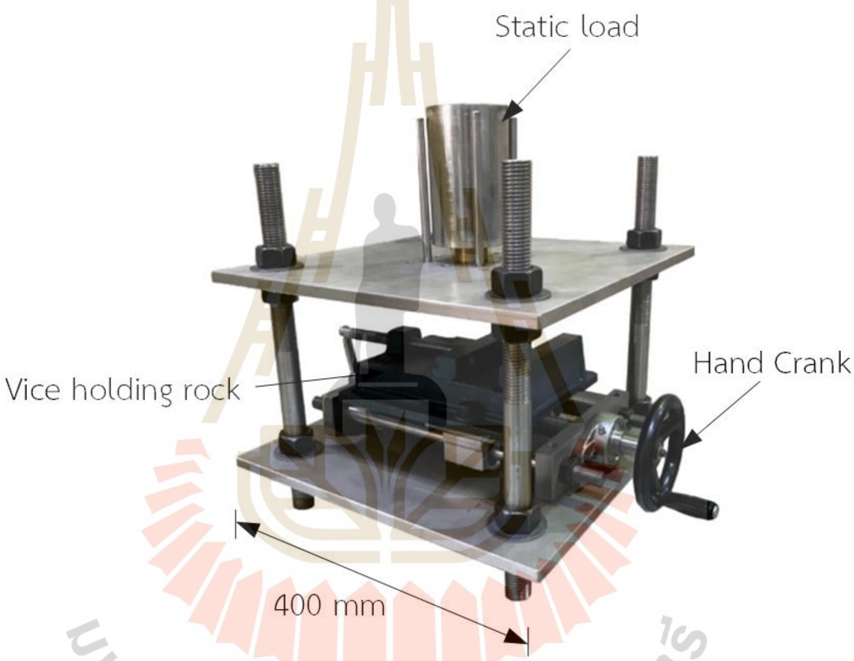

Figure 4.1 Test apparatus used in this study based on West apparatus (West, 1989).

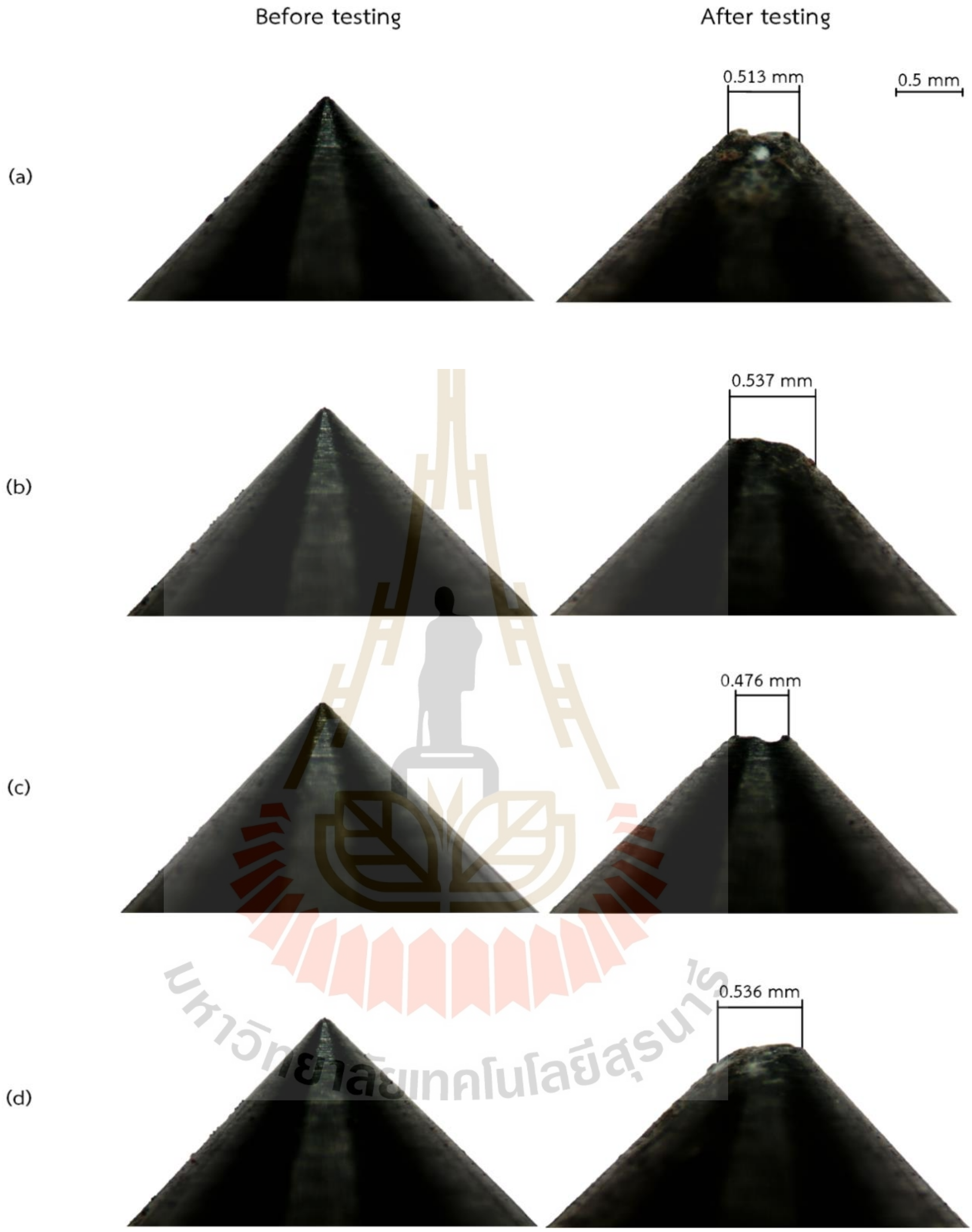

Figure 4.2 Examples wear flat of each stylus tip before (left side) and after (right side) CERCHAR testing on Phuket granite (rough surface), measured its axis in 0° (a), 90° (b), 180° (c), and 270° (d).

4.2.2 CERCHAR abrasivity index (CAI) results

Table 4.1 shows the CERCHAR results from smooth and rough surfaces for 19 specimens. The rough surfaces tend to show higher CERCHAR indexes than do the smooth surfaces.

Table 4.1 CERCHAR abrasivity index (CAI) of all tested rocks.

Rock group	Code	d_i or CAI	
		CAI_r	CAI_s
Clastic	PPSS-1	0.114 ± 0.01	0.095 ± 0.01
	PPSS-2	0.165 ± 0.02	0.140 ± 0.01
	SKSS	0.275 ± 0.01	0.160 ± 0.01
	PWSS	0.296 ± 0.01	0.285 ± 0.01
	PKSS	0.165 ± 0.02	0.110 ± 0.03
Plutonic	GN-1	0.708 ± 0.05	0.535 ± 0.02
	GN-2	0.477 ± 0.02	0.378 ± 0.01
	GN-3	0.285 ± 0.02	0.159 ± 0.01
	AK	0.458 ± 0.01	0.415 ± 0.01
	DR	0.511 ± 0.02	0.402 ± 0.01
Carbonate	MB	0.225 ± 0.05	0.115 ± 0.02
	TV	0.109 ± 0.02	0.089 ± 0.01
	LS	0.162 ± 0.01	0.126 ± 0.01
Sulfate & Chloride	GS-1	0.206 ± 0.01	0.055 ± 0.01
	GS-2	0.022 ± 0.01	0.021 ± 0.01
	RS	0.027 ± 0.01	0.005 ± 0.01
Volcanic	BS	0.242 ± 0.03	0.231 ± 0.01
	VT	0.064 ± 0.01	0.055 ± 0.01
	AD	0.342 ± 0.01	0.317 ± 0.01

4.3 Uniaxial Compressive Strength

The compressive strengths of all rock specimens presented in this thesis are obtained from Chamwon (2020), Phongklahan (2020), and Prasujan (2020), as shown in Table 4.2. The rocks in clastic, volcanic, and plutonic groups tend to show higher compressive strengths than the sulfate & chloride and carbonate groups do.

Table 4.2 Uniaxial compressive strength (σ_c) of all tested rocks.

Rock group	Code	σ_c^* (MPa)
Clastic	PPSS-1	81.43
	PPSS-2	57.83
	SKSS	53.14
	PWSS	70.40
	PKSS	80.08
Plutonic	GN-1	84.47
	GN-2	52.40
	GN-3	37.10
	AK	76.17
	DR	48.20
Carbonate	MB	36.40
	TV	59.64
	LS	54.61
Sulfate & Chloride	GS-1	5.64
	GS-2	5.20
	RS	19.20
Volcanic	BS	79.17
	VT	41.14
	AD	110.11

* σ_c is obtained from Chamwon (2020), Phongklahan (2020), and Prasujan (2020).

4.4 Equivalent Quartz Content

The equivalent quartz content (EQC) representing the hardness of rock can be calculated by Thuro (1997) equation, as follows:

$$EQC = \sum_{i=1}^{n} W_i \times R_i \tag{4.2}$$

$$R_i = \exp\left[(H_M - 2.12)/1.05\right] \tag{4.3}$$

where EQC is equivalent quartz content (%), W_i is mineral amount (%), n is number of minerals, R_i is Rosiwal abrasiveness (%) (Thuro, 1997), H_M is hardness of each mineral based on Mohs scale (Dana, 1912; Hurlbut and Klein, 1977), and 2.12 and 1.05 are constant values from Thuro (1997). This approach presumes that tool wear is predominantly a result of the mineral content harder than steel (Mohs hardness of 5.5), especially quartz (Mohs hardness of 7). To include all minerals of a rock sample, the equivalent quartz content has been determined, meaning the entire mineral contents referring to the abrasiveness or hardness of quartz. Therefore, each mineral amount is multiplied with its relative Rosiwal abrasiveness to quartz (with quartz being 100%; Rosiwal, 1896, 1916).

X-ray diffraction results from Table 3.2 (chapter 3) are used in the calculation of percentage mineral amount (W_i). Example of calculation for EQC for sandstone specimen (SKSS) using equations (4.2) and (4.3) is given below:

$$EQC_{(SKSS)} = \frac{1}{100}\left[(5.55\%\ \text{Feldspar} \times 64.81) + (1.14\%\ \text{Hematite} \times 40.26) + (19.21\%\ \text{Muscovite} \times 1.13) + (74.10\%\ \text{Quartz} \times 100)\right] \tag{4.4}$$

$$EQC_{(SKSS)} = 78.37\% \tag{4.5}$$

Same calculation is applied to all rock specimens using their mineral contents. The equivalent quartz content (EQC) results are shown in Table 4.3. Their values are largest for clastic group, presumably due to the highest quartz contents. The lowest values are obtained from the carbonate and sulfate & chloride groups.

Table 4.3 Equivalent quartz content (EQC) results.

Rock group	Code	EQC (%)
Clastic	PPSS-1	92.92
	PPSS-2	77.90
	SKSS	78.37
	PWSS	85.44
	PKSS	52.71
Plutonic	GN-1	56.81
	GN-2	44.61
	GN-3	49.64
	AK	58.98
	DR	62.58
Carbonate	MB	2.77
	TV	2.52
	LS	3.28
Sulfate & Chloride	GS-1	1.02
	GS-2	3.50
	RS	1.58
Volcanic	BS	22.68
	VT	19.23
	AD	45.86

CHAPTER V

ANALYSIS OF TEST RESULTS

5.1 Introduction

The objective of this chapter is to correlate the CERCHAR abrasivity index with the results obtained from smooth (CAI_s) and rough (CAI_r) surfaces. Uniaxial compressive strength (σ_c) and equivalent quartz content (EQC) are also correlated with CAI. The correlation of CAIr and CAIs can be separated into four categories: correlation between CAI_r and CAI_s, correlation between CERCHAR indexes and rock strength, correlation between abrasivity indices and mineral compositions, and predictability of multiplied factor between CAI_r and CAI_s.

5.2 Correlation between CAI_r and CAI_s

Figure 5.1 shows the correlation of the CERCHAR abrasiveness indexes obtained from rough (CAI_r) and smooth (CAI_s) surfaces for this study. For all rock groups, CAI's of rough surfaces are slightly higher than those of smooth surfaces. The correlation can be represented by:

$$CAI_r = 1.249 \cdot CAI_s \tag{5.1}$$

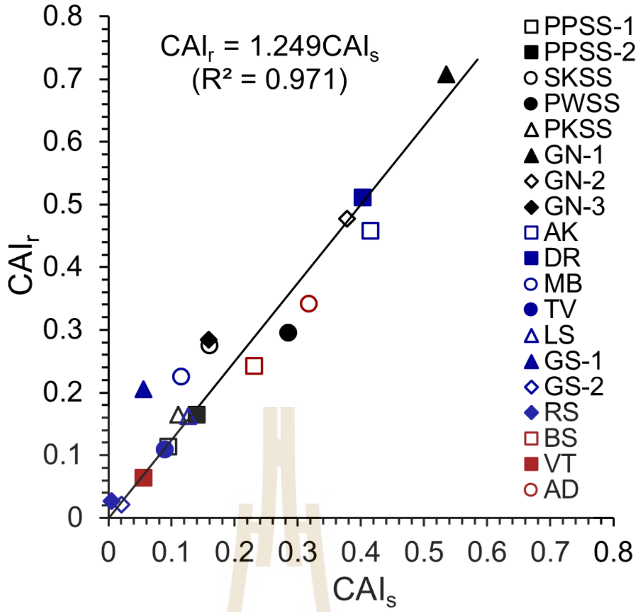

Figure 5.1 Correlation between CAI$_r$ (rough surface) and CAI$_s$ (smooth surface).

Good linear correlation is obtained as indicated by that the coefficient of correlation (R^2) is greater than 0.9 (Figure 5.1). The multiplied factor of 1.249 is higher than those complied by Käsling and Thuro (2010), as reported by Aydın et al. (2016) who propose the multiplied factor of 1.14. This may be due to the fact that the rocks used in this study are classified as soft to medium strong rocks where Käsling and Thuro (2010) correlate CAI$_r$ and CAI$_s$ from a wider range of rock strengths.

5.3 Correlation between CERCHAR Indexes and Rock Strengths

Figure 5.2 plots the CAI_s and CAI_r as a function of uniaxial compressive strength (σ_c) for all rock groups. Both abrasivity indexes correlate fairly well with the rock strength (R^2 > 0.7). CAI_s shows slightly better correlation with the strength than CAI_r does. The correlations can be described by linear equations, as follows:

$$CAI_r = 0.0043 \cdot \sigma_c \quad ; R^2 = 0.719 \tag{5.2}$$

$$CAI_s = 0.0034 \cdot \sigma_c \quad ; R^2 = 0.751 \tag{5.3}$$

The correlation obtained here is close to those obtained elsewhere (He et al., 2016; Ko et al., 2016; Ozdogan et al., 2018).

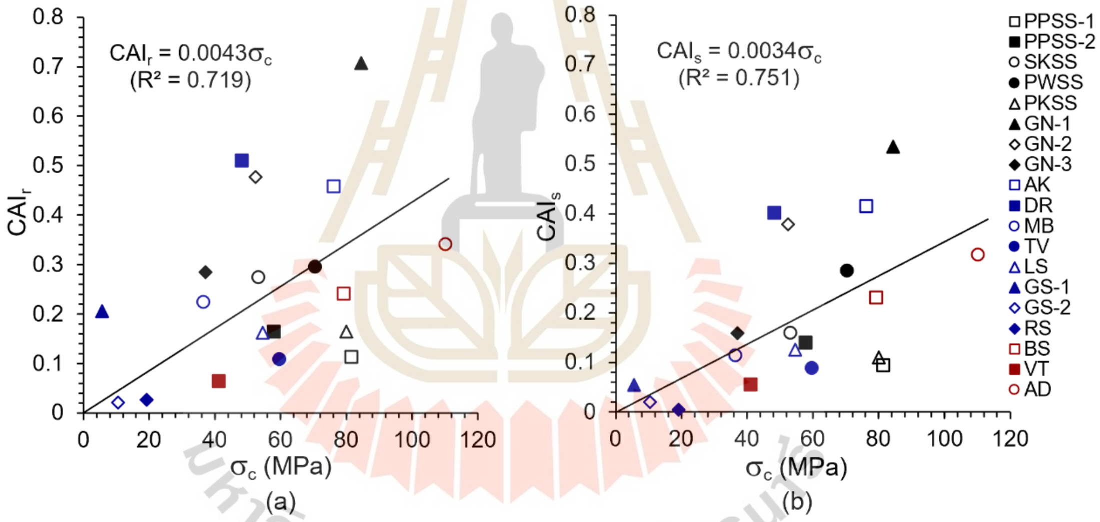

Figure 5.2 Correlation between CAI_r and σ_c (a) and correlation between CAI_s and σ_c (b).

5.4 Correlation between Abrasivity Indexes and Mineral Compositions

The correlation between the abrasivity indices and the widely used equivalent quartz content (EQC) is shown in Figure 5.3. The correlation coefficients are 0.172 and 0.219 for rough and smooth. Poor correlations are obtained. This agrees with the conclusion drawn by Torrijo et al. (2019) and Alber (2008) that no significant correlation is obtained between the two parameters.

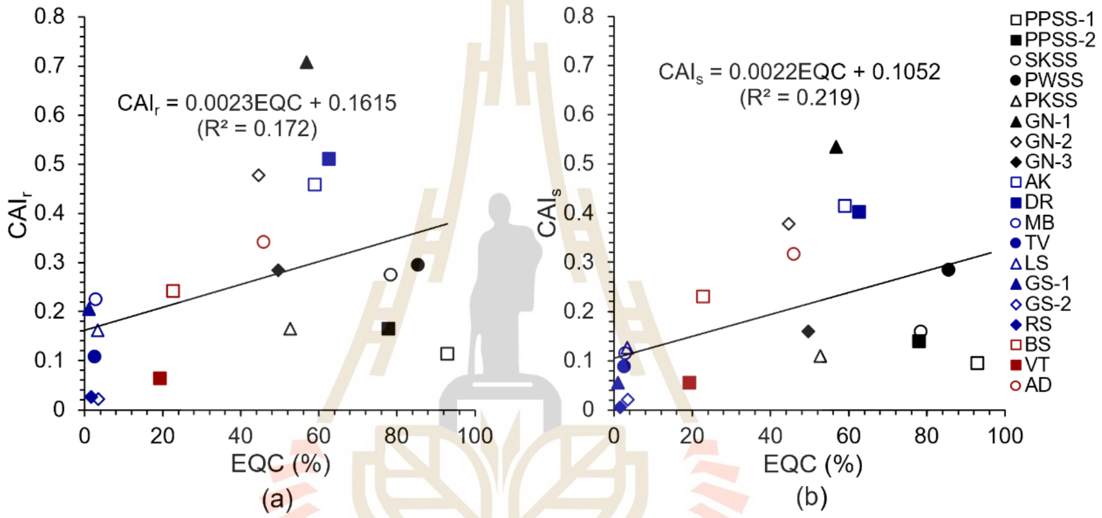

Figure 5.3 Correlation between CAI$_r$ and EQC (a) and correlation between CAI$_s$ and EQC (b).

5.5 Predictability of Multiplied Factor between CAI_r and CAI_s

The relation between CAIr and CAIs obtained here are compared against those reported by Al-Amen and Waller (1994), Aydın et al. (2016), Käsling and Thuro (2010), Yaralı and Duru (2016), and Aydın (2019). The mean misfit (s_i) is determined for each correlation using an equation below (Riley et al., 1998):

$$s_i = [(1/n) (\sum_{j=1}^{n} (X_{j,p} - X_{j,t})^2]^{1/2} \tag{5.4}$$

where $X_{j,p}$ = predicted CAI values of rough surfaces

$X_{j,t}$ = measured CAI values of rough surfaces

n = number of rock specimens

Table 5.1 gives the calculated mean misfits for the proposed multiplied factors. This study gives the mean misfit of 0.054. The lower mean misfits suggest the better correlation between the considered parameters. The rocks used in this study tend to give a better correlation between rough and smooth surfaces than those obtained elsewhere, as shown in the table.

Table 5.1 Mean misfits calculated for each correlation.

Sources	Equation	Mean misfit	R^2
Käsling and Thuro (2010)	$CAI_r = 1.14 \cdot CAI_s$	0.059	0.690
Al-Ameen and Waller (1994)	$CAI_r = -0.01 + 1.00 \cdot CAI_s$	0.089	0.930
Aydın et al. (2016)	$CAI_r = 1.141 \cdot CAI_s - 0.203$	0.241	0.890
Yaralı and Duru (2016)	$CAI_r = 1.1683 \cdot CAI_s - 0.2186$	0.252	0.810
Aydın (2019)	$CAI_r = 1.119 \cdot CAI_s$	0.062	0.960
This study	$CAI_r = 1.249 \cdot CAI_s$	0.054	0.971

CHAPTER VI
DISCUSSIONS AND CONCLUSIONS

6.1 Discussions

The study focused on the correlation of CERCHAR abrasivity index (CAI) between smooth (CAI_s) and rough (CAI_r) rock surfaces. A new mathematical relationship has been derived to obtain a better relationship between the two parameters. Uniaxial compressive strength (σ_c) and equivalent quartz content (EQC) are also correlated with CAI.

Figure 5.1 (chapter 5) shows the linear correlation between the CERCHAR abrasivity index of rough (CAI_r) and smooth (CAI_s) surfaces. The multiplication factor determined here is slightly different from values determined elsewhere, as shown in Table 5.1. This suggests that there are other factors that may affect the scratching process between smooth and rough rock surfaces. Such factors may include grain size, degree of roughness, bonding between grains or crystals, and rock strength.

The CAI values of rough surfaces are slightly higher than those of smooth surfaces. A good linear correlation is obtained, as shown by the correlation coefficient (R^2) of 0.971. The high correlation coefficient (R^2) obtained elsewhere is probably due to the number of rock types (N), as shown in Table 6.1. When the smaller number of rock types (N) is large, the correlation coefficient (R^2) becomes low. In addition, when considering the correlation between CAI_r and CAI_s, the differences in rock texture also affect the correlation coefficient (R^2). The equations with high correlation coefficients (R^2) presented in this study should be more suitable for applying to rocks in Thailand.

Table 6.1 Number of rock types for each correlation.

Sources	Equation	R^2	N
Al-Ameen and Waller (1994)	$CAI_r = -0.01 + 1.00 \cdot CAI_s$	0.930	9
Plinninger et al. (2003)	$CAI_r = 0.99 \cdot CAI_s + 0.48$	0.740	77
Käsling and Thuro (2010)	$CAI_r = 1.14 \cdot CAI_s$	0.690	80
Yaralı and Duru (2016)	$CAI_r = 1.1683 \cdot CAI_s - 0.2186$	0.810	15
Aydın et al. (2016)	$CAI_r = 1.141 \cdot CAI_s - 0.203$	0.890	13
Aydın (2019)	$CAI_r = 1.119 \cdot CAI_s$	0.960	21
This study	$CAI_r = 1.249 \cdot CAI_s$	0.971	19

A fairly good correlation is obtained between CAI and rock strength (σ_c). Both CAI_r and CAI_s increase with increasing σ_c (Figure 5.2). The correlation coefficients are 0.719 and 0.751 for rough and smooth surfaces, respectively. This is consistent with the results of several researchers. In addition, different rock types also result in different strengths. The more variety of rock types and strengths may result in a lower correlation coefficient (R^2).

The hardness of the minerals also affects the correlation coefficient (R^2). The tip of the stylus will be worn out more if it scratches hard minerals, such as quartz, as compared to a softer cementing minerals rock. This implies that higher rock strength may not increasing gild higher CAI value.

Poor correlation is obtained between CERCHAR abrasivity indexes and mineral compositions. Although the nineteen rock types used here are sufficient to determine the linear relationship between CAI_r and CAI_s, they may not be sufficient to establish a good correlation between CAI and a wider range of equivalent quartz contents (EQC) (Figure 5.3). The correlation coefficients are 0.172 and 0.219 for rough and smooth rocks, respectively. Poor correlations are obtained. This is consistent with the conclusion drawn by Torrijo et al. (2019) and Alber (2008) that there is no significant correlation between the two parameters. A wider range of rock properties may be required and the intrinsic variability of rocks also needs to be considered. On the other hand, Moradizadeh et al. (2016) found a fairly good correlation between CAI and EQC. They obtain a correlation coefficient of 0.77, based on bivariate and multivariate regression analysis.

6.2 Conclusions

The outcomes of the results and analysis from this study can be concluded, as follows:

1) Rocks in the north and northeast of Thailand show a linear correlation between CAI_r and CAI_s, where $CAI_r = 1.249 \cdot CAI_s$. Good linear correlation is obtained as indicated by the coefficient of correlation is greater than 0.9.
2) The discrepancy between the multiplied factor obtained here (1.249) and those obtained elsewhere may be due to other coupled factors excluded from this study. Other multiplied factors obtained by other investigators are, for example, 1.14 (Käsling and Thuro, 2010), 1.00 (Al-Ameen and Waller, 1994), 1.141 (Aydın et al., 2016), 1.1683 (Yaralı and Duru, 2016), and 1.119 (Aydın, 2019).
3) Both CAI_s and CAI_r linearly increase with uniaxial compressive strength of rocks, where CAI_s gives slightly better correlation than CAI_r does.
4) Poor correlation is obtained for both CAI_r and CAI_s when they are correlated with the widely used equivalent quartz content (EQC).

6.3 Recommendations for Future Studies

Limitations of the results of this study lead to recommendations for future studies as follows:

1) There are other factors that may affect the scratching process between smooth and rough rock surfaces. These factors include grain size, degree of roughness, bonding between grains or crystals, and rock strength. Further studies are therefore needed to evaluate the coupled their effects.
2) A greater variety of rock properties may be needed to analyze the effects of surface conditions on CAI, especially the correlation between CAI and EQC.
3) The volumes of the scratch grooves from the CERCHAR test on smooth and rough surfaces can lead to different CAI values, which deserve further investigation.
4) The effect of lateral force (F) on the specimens should be studied. The results may reveal the differences of the forces between rough and smooth surfaces. This could lead to explain why the multiplied factors are varied many different investigators.

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