SCHOOL OF MATERIALS AND MINERAL RESOURCES ENGINEERING

UNIVERSITI SAINS MALAYSIA

BRAZILIAN TEST ON MECHANICAL BEHAVIORS OF ANISOTROPIC ROCKS

BY

NURMALIANA BINTI MOHD KHADRI

Supervisor: Dr Hareyani binti Zabidi

Dissertation submitted in partial fulfillment

of the requirement for the degree of Bachelor of Engineering with Honours

(Mineral Resources Engineering)

UNIVERSITI SAINS MALAYSIA

JULY 2017

DECLARATION

I hereby declare that I have conducted, completed the research work and written the dissertation entitled “Brazilian Test on Mechanical Behaviours of Anisotropic Rocks”. I also declare that it is has not been previously submitted for the award of any degree or diploma or other similar title for any other examining body or university.

Name of Student: Nurmaliana binti Mohd Khadri Signature:

Date: 4 July 2017

Witness by

Supervisor: Dr Hareyani binti Zabidi Signature:

Date: 4 July 2017

ACKNOWLEDGEMENT

First and foremost, I would like to thanks to Allah S.W.T. for giving me strength and understanding in order to complete my Final Year Project. Also thanks to my parents for supporting me to complete this project.

Next, I would like to express my appreciation to my supervisor, Dr. Hareyani who had helped me a lot while completing this project by helping me to take a sample at sites. She also continuously supported and gives a spirit of adventure in regard to this research. Because of his guiding and help, this project becomes possible for me to be completed.

Furthermore, a lot of thanks to my Mineral Resources Engineering lecturers and technicians for their help for my project. Sincerely thanks to En Meor, and En. Saarani for their skills in helping at the lab to finish this project. Their cooperation was meaningful for me.

I extend my gratitude to the Quarry Manager at the Lafarge and Hume Cement for their permission to collect the samples at site. Besides, millions of thanks to my lab partner for helping me during my sample preparation and cooperate with me to collect sample together at site.

Finally, big thanks for my parents and Muhamad Zulkhairi bin Zamil for their support and help during my FYP and thesis completion.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

MPa	Megapascal
Mm	milimeter
BTS	Brazilian tensile strength
UCS	uniaxial compressive strength

UJIAN BRAZILIAN KE ATAS PERLAKUAN MEKANIK BAGI BATUAN ANISOTROPIK

ABSTRAK

Batuan anisotropik adalah sifat-sifat batu yang berbeza dengan arah. Ciri-ciri ini boleh menjejaskan dalam pembuatan terowong, operasi kuari dan juga kejuruteraan petroleum dalam mengawal sisihan lubang gerudi, kestabilan dan ubah bentuk. Oleh itu, tahap kelakuan mekanik batuan anisotropik perlu dititik beratkan. Sampel diambil di dua tapak yang berbeza di Perak iaitu LafargeHolcim di Kanthan dan Hume Cement di Gopeng. Sampel kedua-dua tempat mungkin mempunyai ciri-ciri yang sama kerana ia merupakan jenis batuan kapur. Walaubagaimanapun, sampel-sampel ini mungkin berbeza dari beberapa aspek kerana ia berlaku di tempat yang berbeza. Kajian eksperimen dalam projek ini memberi tumpuan kepada corak kekuatan kegagalan dan corak pecahan batuan anisotropik di bawah ujian Brazil.Pada akhir eksperimen ini, kekuatan kegagalan dikaitkan dengan orientasi lapisan relatif. Kekuatan kegagalan juga dikaitkan dengan relatif pengaktifan lapisan panjang patah bagi sampel yang diuji. Semakin bertambah sudut semakin kurang kekuatan kegagalan. Kekuatan tegangan tertinggi terjadi pada 0º dimana 16.77 Mpa dan kekuatan yang paling rendah terjadi pada 75º dimana 5.68 Mpa untuk sampel LafargeHolcim. Untuk Hume Cement, Kekuatan tegangan tertinggi terjadi pada 0º dimana 13.23 Mpa dan kekuatan yang paling rendah terjadi pada 75º dimana 6.42 Mpa.

BRAZILIAN TEST ON MECHANICAL BEHAVIORS OF ANISOTROPIC ROCKS

ABSTRACT

Anisotropic rocks are the properties of rock which vary with direction. This property may affect tunnelling, quarrying operation and also petroleum engineering in controlling borehole deviation, stability and deformation. The samples are taking at two different sites in Perak which is LafargeHolcim at Kanthan and Hume Cement at Gopeng. The sample at these two sites maybe same in properties as there are the limestone. However, it may also be different at some aspect since it is occurred at the different places.The experimental study in this project focused on the failure strength and fracture pattern of anisotropic rocks under Brazilian test. , At the end of this experiment, failure strength is expectedly correlated with relative layer orientation. The failure strength is also expectedly correlated with relative layer activation fracture length for the tested sample. The higher the inclination angle the lower the failure strength. The highest tensile strength occurred at 0º which is 16.77 MPa and the lowest occurred at 75º which are 5.68 MPa for LafargeHolcim. For the Hume cement, the highest tensile strength occurred at 0º which is 13.23 MPa and the lowest occurred at 90º which are 6.42 MPa for Hume Cement.

CHAPTER 1

INTRODUCTION

1.1 Research Background

Brazilian test is a geotechnical laboratory test that used for indirect measures of tensile strength. Due to its simplicity and efficiently it is a common method that used laboratory testing method in investigating for rock. The procedure is simple and the sample preparation is also easy compared to the other test.

This test is used to determine the mechanical behaviour of anisotropic rock. Anisotropic is the rock near the earth surface which has mechanical properties that can change as a function of the direction. For anisotropic rock, the failure mechanism of rock material is more problematic due to their complex mineralogical. Rock anisotropy is a critical factor in controlling the stability, deformation and failure. It is also affects the fracturing and fracture propagation. Furthermore, anisotropy is a characteristic of intact foliated metamorphic rock and intact laminated, stratified or bedded sedimentary rocks. Study on anisotropy is important in engineering field of civil, mining and petroleum. However, it is often poorly understood.

Scientists study the properties of anisotropic rocks by many ways using Brazilian test. Many attempts have been made to study the strength and failure of inherently anisotropic rocks.

1.2 Problem Statement

This experiment is focused on the problem of layer orientation in rocks sample. There are 3 types of fracture that will occur due to the different inclination angle test. The fractures are central fracture, non-central fracture and layer orientation fracture. As results, the mechanical behaviour may occur due to this effect.

Furthermore, this project also focused in the tensile strength occurs to the anisotropic rocks. It is illustrate the effect on the failure strength on macro scale and fracture pattern of the sample. Anisotropy is importance in engineering application as the stability of underground excavation, slope stability, breakage of rock and borehole deformation. Due to anisotropy properties, the fracture and the tensile strength will be different because it is vary with direction. As the theory, the maximum tensile strength occurred at or near $\theta = 0^{\circ}$ whereas the minimum tensile strength value occurred at $\theta = 90^{\circ}$.

1.3 Study Areas

The rock samples are taken at 2 different places which are at quarry site of LafargeHolcim (Kanthan) and Hume Cement (Gopeng). Both sites are placed at Perak.

For LafargeHolcim, it is a manufacturer of building materials (primarily cement, aggregates and concrete). It is merge of two leading world's company of cement that is Lafarge which based at French and Holcim which is a Swiss-global company.

Gunung Kanthan which located at Chemor is the quarry site for LafargeHolcim Kanthan Plant. It is the limestone quarry where the samples are taken.

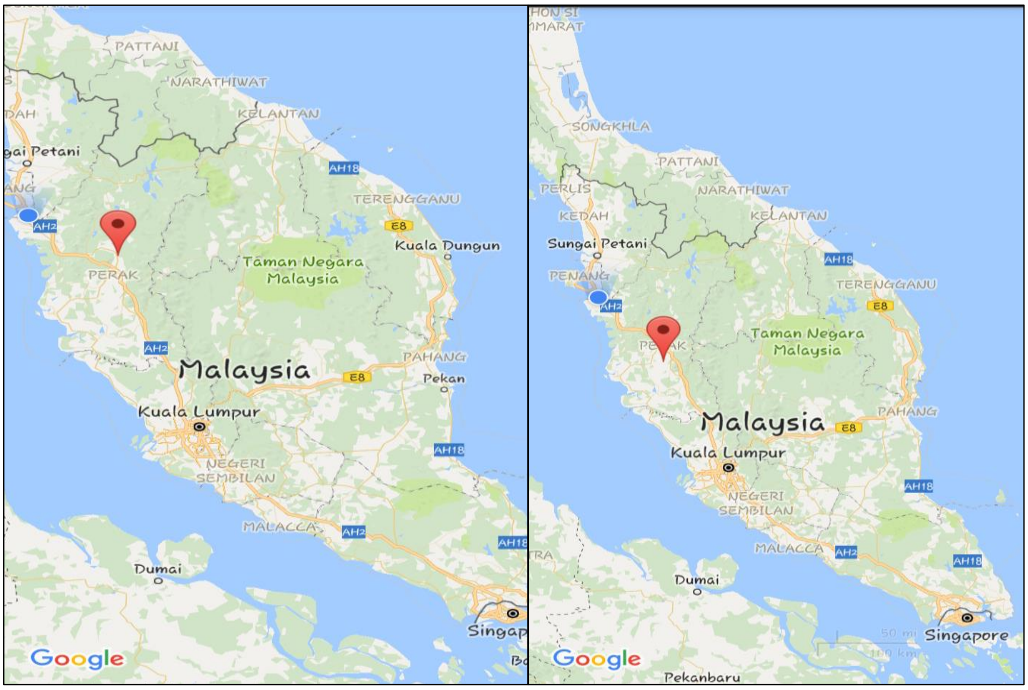

Figure 1.1 Map of Peninsular Malaysia showing state boundaries and the position of Perak, Gunung Kanthan and Hume Cement.

For the Hume Cement, it is located in Gopeng. It is the same company as LafargeHolcim which produce building material such as cements. It is a new company which operate for almost 4 years. The quarry is the ex-pond of tin mining.

The pinnacle of the quarry is actually at the ground level since the limestone is excavated after the water of the pond is pump out. Therefore, it has a bit different of physical appearance of limestone compared to LafargeHolcim. The rock sample at the Hume Cement is quite massive compare to the LafargeHolcim. It is a bit difficult to determine the stratified rock that parallel with the parameter required. Figure 1.2 and Figure 1.3 shows the area that the sample are taken at Hume Cement while Figure 1.4 shows the area that the sample are taken from LafargeHolcim.

Figure 1.2: Site of Hume Cement where sample is collected

Figure 1.3: Collecting sample at Hume Cement's site

Figure 1.4: LafargeHolcim's site where samples are collected.

Figure 1.5: Area where the sample are collected at LafargeHolcim.

1.4 Research Objectives

The research is conducted based on the purpose of:

I. To study the basic properties of the anisotropic rocks
II. To study the fracture pattern occurred of an anisotropic rock.
III. To analyse the tensile strength of anisotropic rock

1.5 Research Approach

The project was carrying out at the lab of the School of Material and Mineral Resources Engineering. The samples are taken at LafargeHolcim and Hume Cement which located at Perak.

There are many way to study the anisotropic rock properties whether using triaxial compression, point load test, UCS, direct shear stress and Brazilian test. This project studies on the properties of anisotropic rock using the Brazilian test. Unique characteristics of anisotropic behaviour have important impacts on the fracture pattern. Fracture pattern and tensile strength of the anisotropic rock were determined using the Brazilian test. The problem that related to the anisotropic rock more difficult to isotropy because of the number of variables in anisotropy problems is several times more than isotropy problem.

1.6 Outline of Thesis

This thesis is divided into five chapters. The first chapter is briefly discussed about the general idea of this project and its purpose. The second chapter is the literature review which is the information is extracted from the journals and books. The chapter three is methodology which will be discussing about the way to conduct the research. Besides, it also discussed the apparatus and the material used for the research. In the chapter four, this thesis discuss about the result and discussion of the Brazilian test based on the fracture pattern and the tensile strength of the anisotropic rocks. In chapter five, it is respectively state the conclusion and the recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Anisotropic rocks are the properties which have directional mechanical behaviour. These anisotropic characteristics are originated from mineral foliation in metamorphic rock, discontinuities in the rock mass and stratification in sedimentary rocks. These properties can give effect to the engineering application.

2.2 Basic Properties of Anisotropic Rocks

In this research, it focused on the strength and fracture pattern of the anisotropic rocks. In order to understand the effects of the layer orientation on the strength and the fracture pattern, the anisotropic rocks had been studied. Polar diagrams are a convenient way to represent the degree of anisotropy in two dimensions.

Rocks which have properties that vary with direction are said as anisotropic. It is also refer to the properties of a material that is dependent on the direction. Besides, anisotropic defined as the presence of different properties in different directions.

A mineral can be considered as anisotropic if it can allow some light to pass through it. It can affect the polarization of light and the velocity also different and there is also double refraction where the light will split into two ways. In anisotropic mineral, double refraction can lead to uniaxial or biaxial.

Usually intact rock is anisotropic due to its geological origin and history. These anisotropic characteristics are originated from mineral foliation in metamorphic rock, discontinuities in the rock mass and stratification in sedimentary rocks. However, the anisotropic created by the discontinuities will have much greater engineering significance. Furthermore, several joint sets will cause anisotropy more complex.

This rock anisotropy can give effects to many fields such as civil and mining engineering where the stability of underground excavation, surface excavation and foundation can be affect by anisotropy. Besides, it also affects drilling, blasting and rock cutting. Furthermore, it can induce directional fluid flow and contaminant transport. Rock anisotropy can be critical factors in petroleum engineering in controlling borehole deviation, stability, deformation and failure. It also impact fracture propagation and fracturing. Therefore, the degree of mechanical behaviour of anisotropic rock needs to be aware in order to decide whether it is relevant or not to consider the anisotropy before start any certain operations (Chan,Pan, Amadei,1998)

2.2.1 Constitutive Model of Anisotropic Rocks.

As shown in Figure 2.1, it is the global (x',y',z') and local (x,y,z) coordinate system. A local coordinate system is attached to the plane of anisotropic of the rock media. The y-axis is the axis of rotation symmetry that is normal to the isotropic planes and the x and z axes are contained within the isotropic plane. The z'-axis coincides with the z-axis.

For a anisotropic rocks in a local and global coordinate,generalized Hooke's law can be given in the following tensor equation:

$$\varepsilon = S\sigma \tag{1}$$

Where,

ε = strain

S = elastic compliance

σ = stress

Equation (1) can be also expressed in matrix form as

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{zx} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E} & -\frac{v'}{E'} & -\frac{v}{E} & 0 & 0 & 0 \\ -\frac{v'}{E'} & \frac{1}{E'} & -\frac{v'}{E'} & 0 & 0 & 0 \\ -\frac{v}{E} & -\frac{v'}{E'} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G'} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2(1+v)}{E} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G'} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix} \tag{2}$$

In the compliance matrix, there are five independent elastic constants exist. *E* is the elastic moduli in the plane of isotropic and *E'* are the elastic moduli in the direction normal to it. While *v* is the Poisson's ratios that characterize the lateral strain response in the plane of anisotropic to a stress acting parallel and *v'* is the Poisson's ratios that characterize the lateral strain response in the plane of anisotropic to a stress acting normal to it. *G'* is the shear modulus in the plane normal to the plane of anisotropic.

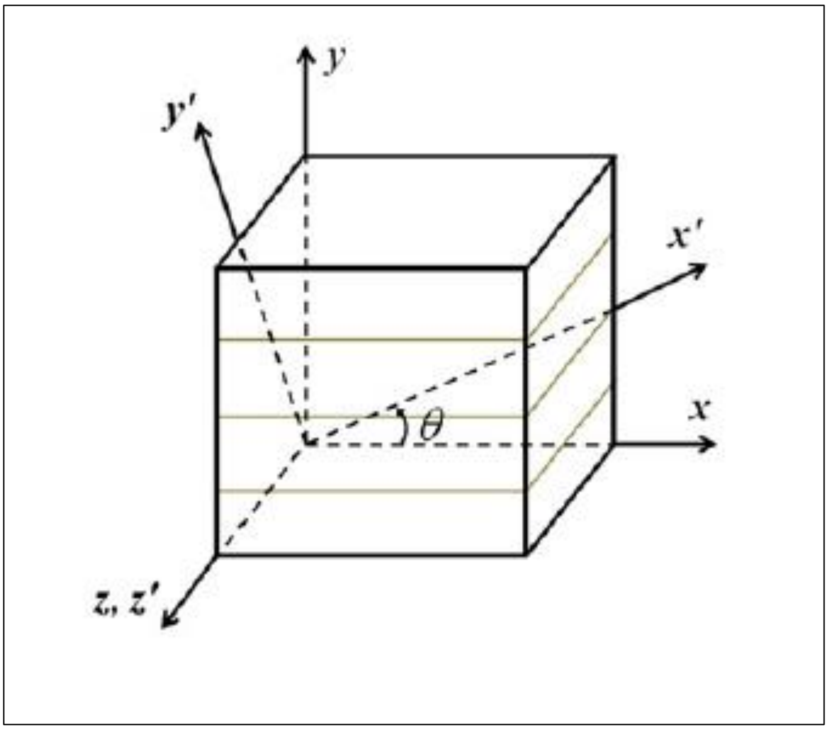

Figure 2.1: Definition of global and local coordinates in anisotropic rocks

The generalized Hooke's law in global coordinates is expressed as follows:

$$\varepsilon' = S'\sigma' \qquad (3)$$

Equation (3) can be expressed in matrix form as

$$\begin{bmatrix} \varepsilon_{x'} \\ \varepsilon_{y'} \\ \varepsilon_{z'} \\ \gamma_{y'z'} \\ \gamma_{z'x'} \\ \gamma_{x'y'} \end{bmatrix} = \begin{bmatrix} S'_{11} & S'_{12} & S'_{13} & S'_{14} & S'_{15} & S'_{16} \\ S'_{21} & S'_{22} & S'_{23} & S'_{24} & S'_{25} & S'_{26} \\ S'_{31} & S'_{32} & S'_{33} & S'_{34} & S'_{35} & S'_{36} \\ S'_{41} & S'_{42} & S'_{43} & S'_{44} & S'_{45} & S'_{46} \\ S'_{51} & S'_{52} & S'_{53} & S'_{54} & S'_{55} & S'_{56} \\ S'_{61} & S'_{62} & S'_{63} & S'_{64} & S'_{65} & S'_{66} \end{bmatrix} \begin{bmatrix} \sigma_{x'} \\ \sigma_{y'} \\ \sigma_{z'} \\ \tau_{y'z'} \\ \tau_{z'x'} \\ \tau_{x'y'} \end{bmatrix} \qquad (4)$$

The compliance matrix in equation (4) can be obtained through the tensorial transformation, which involves direction cosine with θ signifying counter clockwise rotation.

2.2.2 Failure Modes of Anisotropic rocks

In the development of a failure criterion, the failure modes of rock specimens are test under the different orientation angle and under different confining pressure. It is an ideal failure criterion if it is able to predict the state of stress at failure and the failure mode. The failure mode of anisotropic rock under the triaxial test is influenced by the orientation of the stresses and the confining pressure. Therefore, it is more complicated rather than isotropic rocks. Many researchers described in detail the failure modes of anisotropic rock into two modes as follow:

a) Sliding along the discontinuities.
b) Fracture through the rock material.

Jaeger's criterion is mainly based on the simplified assumption of failure modes described above.

2.2.3 Effects of Geometric Anisotropy on Permeability Anisotropy

The distinct element method is used to carry out the numerical modelling of fluid flow through fractured rock. In the flow model, fractures are assumed to have a fixed, uniform aperture and the flow rate through the fracture, *qj*, is calculated by the cubic law:

$$qj = kja^3\frac{dH}{dL} \quad (4)$$

Where:

kj = the permeability factorof a fracture, *kj* = 1/(12μ), μ is the dynamic viscosity

a = the fracture aperture.

$\frac{dH}{dL}$= the pressure gradient along the contact length, L.

2.2.4 Effect of Strength Anisotropy on the Stability of Slopes

The effect of strength anisotropy of geomaterials is normally due to the presence of the weak planes in the material which on the stability of the slope. To incorporate with the effects of weak planes in finite element simulation, two different approaches were invented. Where the approaches as below:

I. The weak planes were introduced to the model by inserting a joint network in the finite element model.

II. One of the constitutive models of the material included the planes of weakness.

Based on from the approached made, it was shown that the stability of slopes is dependent on the presence and configuration of the weak planes in the material. The shape of the possible slip surface is likewise impacted by the introduction of the weak planes. The got numerical comes about utilizing the two methodologies were in a decent concurrence with each other in assessment of the factor of safety of slopes.

2.2.5 Effect of Anisotropy on the Analysis of Overcoring Measurements

Overcoring technique is the borehole relief method where it is a method and procedure to separate rock sample from the stress field in the surrounding rock by coring. Strain or displacement measurements on the specimen thus separated are recorded in the vicinity of the point at which the state of stress has to be determined. This requires the stress field to be homogeneous all through the zone of enthusiasm before the estimations are performed which is a sensible presumption in the absence of heterogeneities or major geological in the rock mass.

Figure 2.2 shown the step that commonly involved when measuring in situ stress by overcoring with instrumented devices. Firstly, a large diameter of hole is drilled to the required depth in the volume of rock in which stresses have to be determined. Secondly, a small pilot hole is drilled at the end of the previous hole before an instrumented device is inserted into the pilot hole. Lastly, the large diameter hole is continuing which will result changes in strain or displacement within the instrumented devices are recorded.

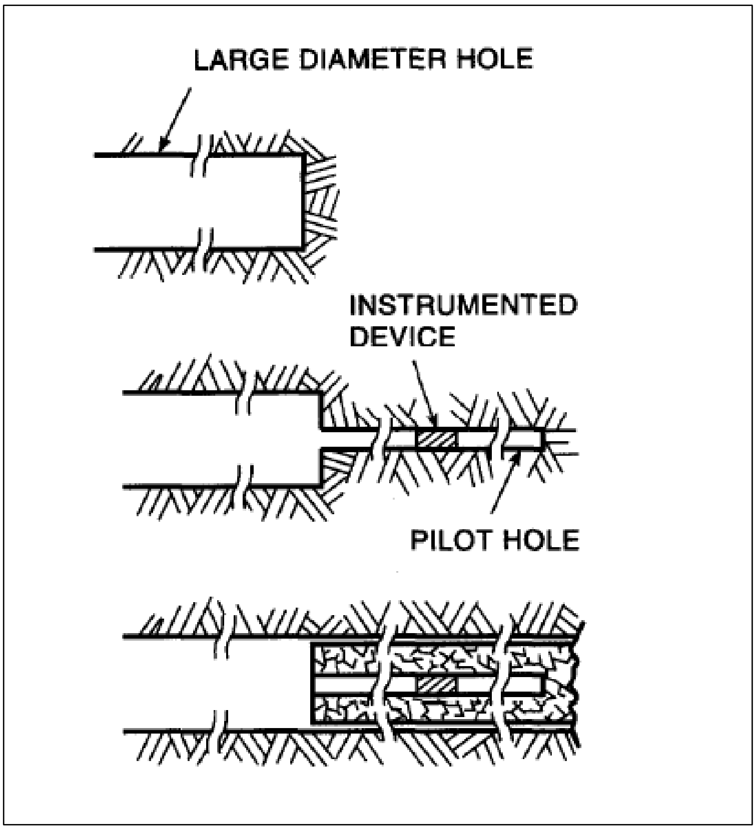

Figure 2.2: Overcoring technique with instrumented devices

The successful interpretation of this test depends to a great extent on the ability:

I. To establish a stress-strain relationship for the rock

II. To be able to determine rock mass properties from tests on core samples.

2.2.6 Effects of Anisotropic on Underground Oil Storage Caverns

Oda's method for determining the anisotropic permeability is used for an underground oil storage cavern. In this method, anisotropic permeability of the site is determined from fracture orientation distributi0n and in situ stress obtained from field survey. The effect of anisotropic permeability on water pressure, water quantities and critical gas pressure need to be studied properly. In this method, the researcher concludes that the rock stability around cavern crown decrease as the anisotropy in permeability increase.

2.2.7 Crack Pattern in Anisotropic Rock Sample (Normal to Foliation)

For the macroscopic pattern, there are big cracks parallel to foliation. There are big cracks parallel to foliation, which are running normal to the sidewalls of the borehole reaching up to 40 mm into the sample. Also visible are small cracks, which are oriented parallel to the bottom of the borehole. They reach down to 5 mm under the bottom. Cracks running slanting to the foliation down to 20 mm into the specimen can rarely be detected.

For microscopic crack pattern, in the thin sections most of the cracks run parallel to the bottom of the borehole thus parallel to foliation (Figure 2.3). The cracks nearly always use lanes of mica, which are zones of weakness in the rock sample. Cracks across mineral components, like quartz, feldspar or biotite can rarely be detected. Stair-like fissures use the shortest distance between mica-rich layers. An opening of mica layers is visible which may be performed by the rotary, and therefore shearing, action of the drill. These large cracks allow large fragments to be removed by the flushing.

Cracks can be found on the sidewalls of the borehole, which run normal to the hole as well as parallel to the bottom. The normal cracks along mica layers reach up to 40 mm into the rock. The cracks, which are running parallel to the sidewalls of the borehole go across the mineral components and only rarely use cleavage or zones of weakness. No opening of the grain structure or tearing out of mineral components along grain boundaries can be seen. Cracks which are running normal to the bottom of the borehole are rarely found. They are produced by stress during percussion. Cracks slanting to the mica layers were found very rarely.

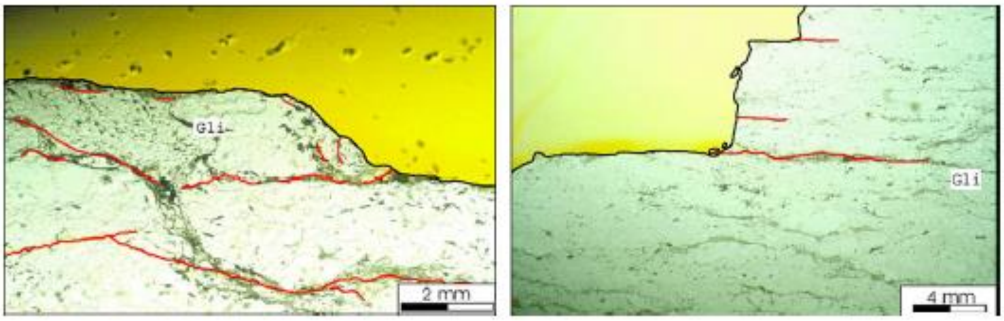

Figure 2.3: Example of thin section of the granite-mylonite sample. Drilling direction normal to foliation, cracks traced in red colour.

2.2.8 Crack Pattern in Anisotropic Rock Sample (Slanting to Foliation)

For macroscopic pattern, typical large cracks in coarse-grained rock types (syenite) are oriented normal to the bottom of the borehole, not in the foliation. If it is cut 60 mm deep into the rock, cracks running 20 mm along the foliation can be rearly seen. In the fine-grained, very tight foliated granite-mylonite no cracks in the macroscopic size could be found.

For microscopic pattern, In the thin sections, a correlation of the crack patterns between the spacing of the foliation and the grain size could be detected. In the very tight foliated, fine-grained granite-mylonite, the cracks run along the mica layers as zones of weakness (Figure 2.4). Cracks across mineral components are rarely found since they are not zone of weakness. At the bottom of the borehole a roof-shaped or stair-like structure of the crack patterns could be detected. The opening of the mica layers seems to be caused by the percussive process and the shearing process of the bit caused the breakout of the fragments. An angle of about 15 degrees seems to be useful to break out the fragments. In the widely foliated coarse-grained syenite, cracks parallel to the surface are common. Cleavage of mica and feldspar as zones of weakness are rarely used. The cracks don't follow the foliation as a zone of weakness. Often cracks occur across mineral components, which are oriented parallel

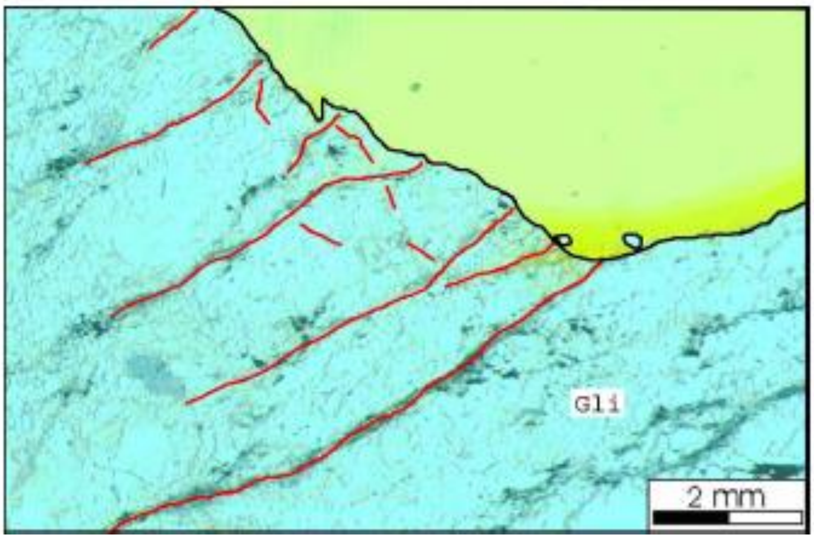

Figure 2.4: Example of thin section of the granite-mylonite sample. Drilling direction slanting to foliation, cracks traced in red colour.

to the bottom of the borehole. Cracks normal to the bottom are produced by the percussion energy of the hammer. They have already been detected as macroscopic cracks.

2.2.9 Crack Pattern in Anisotropic Rock Sample (Parallel to Foliation)

For macroscopic crack pattern, when drilling parallel to foliation, cracks mainly develop in the foliation and not parallel to the borehole bottom. Cracks of up to 50 mm could be observed. Also cracks in the edges of the bottom could be detected running up to 30mm into the rock sample.

For microscopic pattern, the small cracks run parallel to the surface (normal to the foliation). The cracks develop through all mineral components. Focusing on the fragments (chips), mechanical stress caused by shearing could not be detected. They were broken out without any movement along the bottom of the borehole. It seems that the percussion drill caused a very high stress state between the buttons, which is high enough to tear out the chip. In those only 1 mm sized cracks could be found, which are parallel to the foliation. They were evidently caused by a previous percussion process seconds before. Cracks parallel to foliation are common since they use mica layers as zones of weakness spreading down to 10 mm into the sample (Figure 2.5). Macroscopic cracks range up to 50 mm as described above. Cracks parallel to the sidewalls of the borehole could rarely be detected, but those that were are probably remnants of the previous percussive action seconds before.

To summarize the crack patterns for the three anisotropic cases, refer Figure 2.6. For the macroscopic crack patterns, Knowing that drilling performance is best normal to foliation and worst parallel, the macroscopic crack patterns support the following statements:

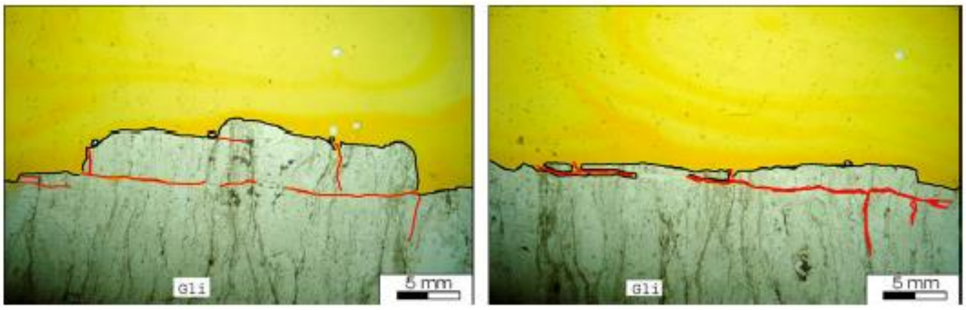

Figure 2.5: Example of thin section of the granite-mylonite sample. Drilling direction parallel to foliation. Cracks traced in red colour.

When the direction of drilling is normal to the orientation of foliation, rock material is compressed normal but sheared parallel to it. Although cracks will develop radial to compression, the cracks parallel to the bottom of the borehole will be used for chipping. Usually in this case the highest drilling velocities are obtained because of the favourable schist orientation. Drilling is controlled by the shear strength of the foliated rock material. This causes large sized chips and a maximum drilling performance.

If the drilling axis is oriented parallel to foliation, compression is also parallel to foliation but shear stress is normal to it. Less and smaller cracks (observed 1 mm) develop for reasons of higher strength normal to the weakness planes. Drilling is controlled by the tensile strength parallel to the foliation producing small sized fragments and minimum drilling performance.

Generally, drilling is controlled by the dip angle of foliation, submitting medium sized fragments during the crushing process. Drilling performance is - by geometrical reasons - mainly a cosine function of the dip angle. In the parallel case, rock properties are the highest and drilling rates are low. In addition blasting conditions are often related with drilling. Therefore, if the tunnel axis is parallel to the main foliation, drilling and blasting conditions are expected to be very poor.

For microscopic crack pattern, in the thin sections, there seems to be a relationship between the crack pattern and the direction and condition of the foliation. The crack pattern in the widely foliated quartz-syenite sometimes propagates along the mica layers, but it is not compelling. The cracks develop parallel to the surface and use foliation only if the foliation runs along a surface-parallel crack. Mostly they propagate across mineral components. The crack pattern is similar to those from isotropic rocks. In the granite-mylonite samples, the spacing and the condition of the foliation is important. It is postulated that the better the condition of the foliation (clear mica layers) and the closer the foliation is, the more the cracks run along the mica layers in the microscopic scale. This means that the mica layers were almost exclusively used as zones of weakness from which cracks developed.

The above confirms that the degree of anisotropy plays a key role in rock fragmentation (Thuro 1997, Plinninger & Spaun 2002, Thuro & Plinninger 2003). The effect of the direction of the foliation on rock fragmentation has yet to be established.

2.3 Fracture Pattern Occurred

Due to the deposition, when it is subjected to the stress, most rocks of sedimentary origin that occur in the upper layers of the earth's crust exhibit some degree of anisotropy properties. The research of the effect of anisotropy on rock behaviour is necessary since the deformation and fracture

The rock layers for this experiment are inclined at five different angles ranging between 0º (perpendicular to the loading direction) to 90º (parallel to loading direction). The five different angles are 0º, 30º, 60º, 75º and 90º.

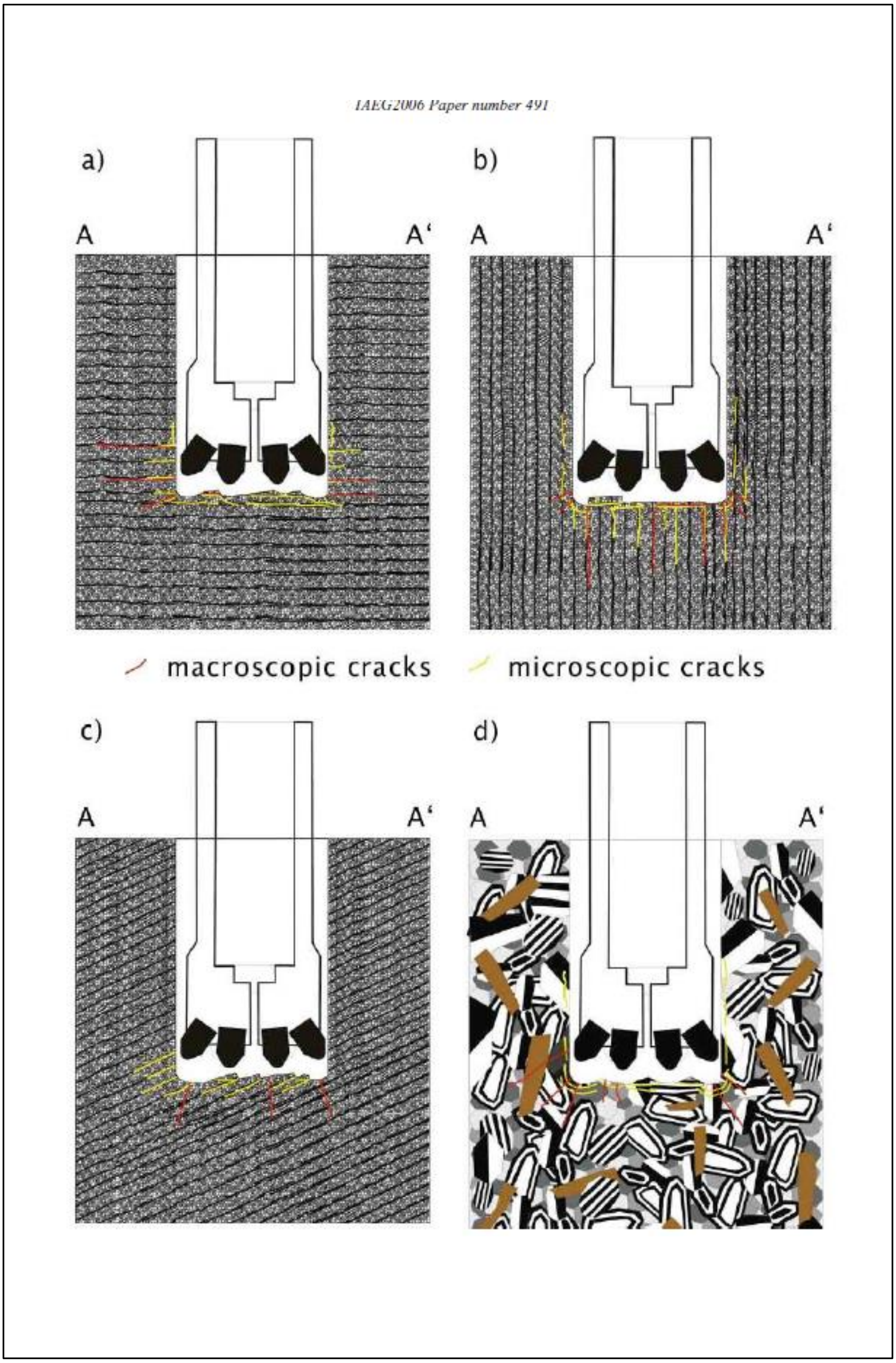

Figure 2.6: Crack pattern in a) anisotropic rock drilled normal to foliation; b) drilled parallel to foliation; c) drilled slanting to foliation; d) isotropic rock.

Theoretically, when the layers are horizontally or semi horizontal, the fracture is mainly through the stronger material while when the inclination angle increase, the fracturing process make use of the layers, where one could expect that they have weaker mechanical properties. Besides, it is possible the sample fail also in shear and not purely in tension.

Based on the previous studies, it show that if the angles θ < 50º, the fracture through the intact materials should dominant while for the sample with θ < 50º, the fracture parallel to the layer should be dominant (see Figure 2.8).

Based on the sample after failure, different types of fractures are observed (see Figure 2.7). Similar to the idea introduced by Szwedzicki (2007) for UCS tests, different fracture types were suggested by Tavallali (2013) where:

i. Layer orientations occur if some fractures are parallel to the isotropic layers
ii. Central fractures can be determine if some fracture are roughly parallel to the loading direction and they are located in the central part of the sample between two lines. It is arbitrarily defined as 10% of the diameter on both sides of the central line.
iii. Non-central factures occur if they do not correspond to layer activation where the fractures outside the central part are observed.

However, in most cases more than one of fracture type occurs in the same experiment. If this occurs, the total lengths of the fractures were measured in the various rock specimens and the relative fracture length of each category in comparison to the total length of fractures was calculated. If the major part of a curved shape fracture is outside central zone, the entire length plus the small portion in the central zone is put into the total sum of non-central fractures Tavallali (2007).

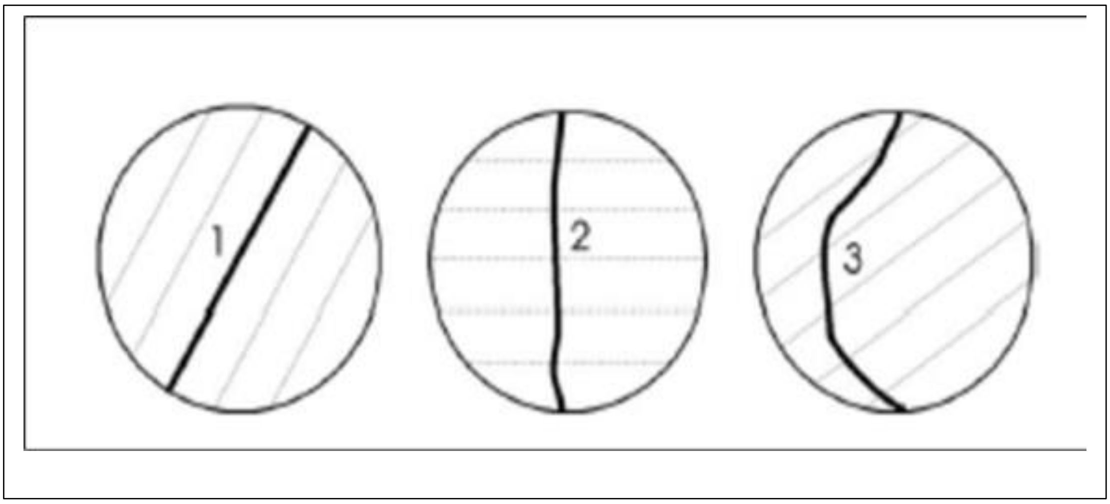

Figure 2.7: Schematic representation of different fracture types in Brazilian test. (1) Layer activation, (2) central fracture, and (3) Non-central fracture (Tavallali, 2013)

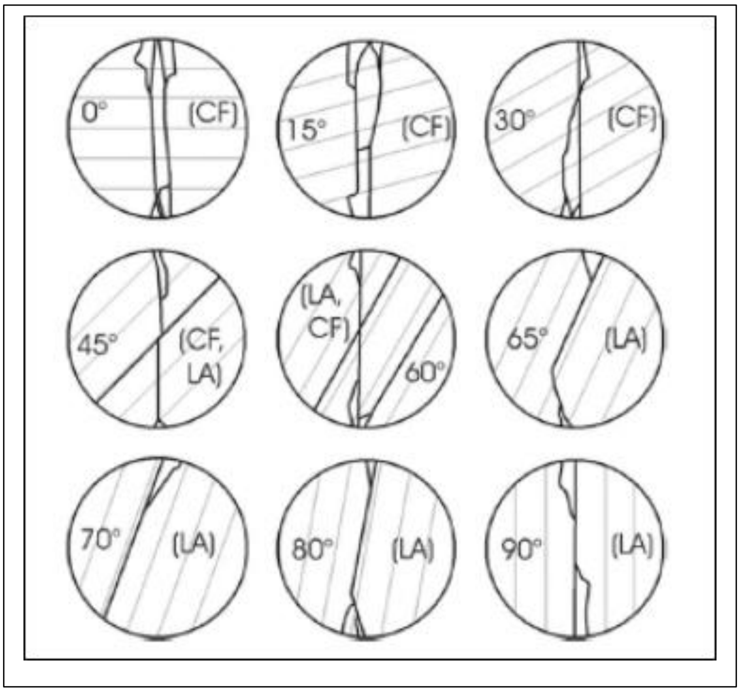

Figure 2.8: Observed failure patterns of Brazilian tests for Different values of the inclination angle (one typical sample of reference sub-type for each group). The predominant mode is put in parentheses, CF=Central fracture, and LA=Layer activation. (Tavallali, 2013)

2.3.1 Rock Fracture Mechanics

Rocks are inherently inhomogeneous and normally anisotropic materials. In civil and mining engineering project, the phenomenon of brittle failure is frequently occurring. This is due to the environmental factors whether it is water and confining pressure, particularly in waste disposal and storage applications (Morteza Ghamgosar, David J. Williams, Nazife Erarslan, 2015).

The numerical analysis demonstrates that when temperature is increase within the rock mass, it can induce stress and as results, fracture will propagate along anisotropic features. In Linear Elastic Fracture Mechanics (LEFM), three fundamental deformation modes at the crack tip exist as shown in Figure 2.10.

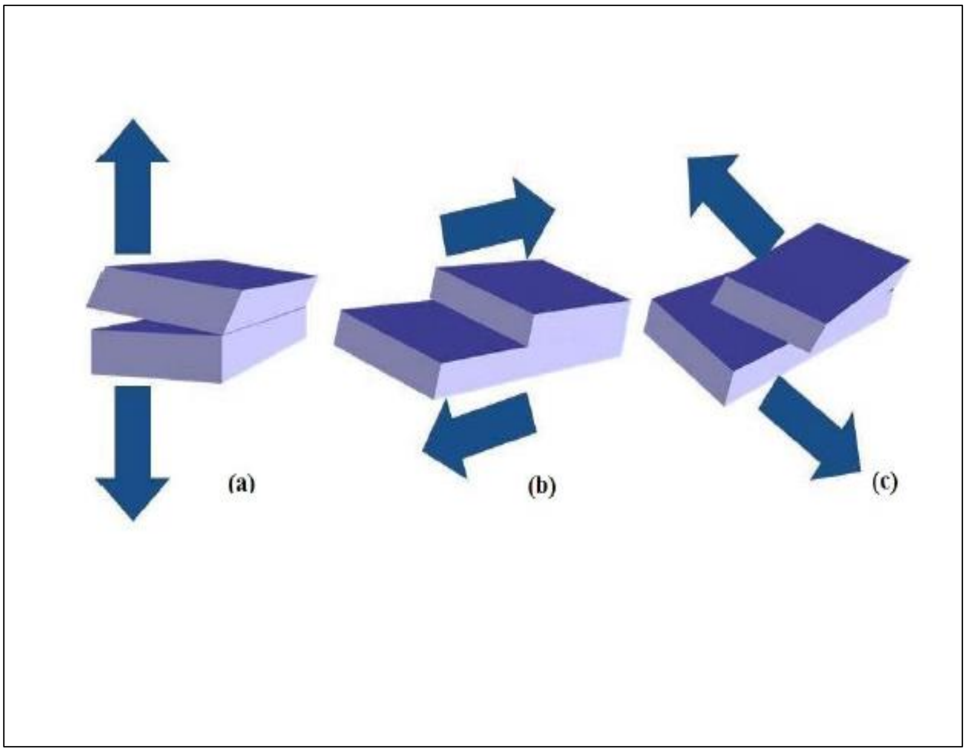

Figure 2.9: Fundamental modes of LEFM fracturing (Morteza Ghamgosar, David J. Williams, Nazife Erarslan, 2015).

As shown in the Figure 2.9 above, it is indicates:

a) Pure tensile fracturing

b) Pure shear fracturing