SLAKE DURABILITY INDEX TESTS OF THIRTEEN ROCK TYPES UNDER DRY, WET AND ACIDIC CONDITIONS

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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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การทดสอบดัชนีการสึกกร่อนได้ถูกดำเนินการเป็นจำนวน 100 รอบเพื่อประเมินการสึกกร่อนของหินจำนวน 13 ชนิด ที่ถูกแบ่งออกเป็น 4 กลุ่มคือ หินบะซอลต์ หินคาร์บอเนต หินทรายและหินแกรนิต การทดสอบในระยะยาวมุ่งเน้นเพื่อจำแนกอัตราการเสื่อมสภาพของหินที่มีความแข็งใกล้เคียงกัน รอบทดสอบจำนวนสามชุดถูกดำเนินการภายใต้สภาวะแห้ง เปียกและความเป็นกรด ผลที่ได้ระบุว่าการเสื่อมสภาพของหินคาร์บอเนต โดยเฉพาะอย่างยิ่งหินทราเวอร์ทีนเพิ่มขึ้นอย่างมีนัยสำคัญเมื่อหินอยู่ภายใต้น้ำและกรด ปริมาณออกไซด์เหล็ก จำนวนรูพรุนและช่องว่างช่วยเร่งอัตราการเสื่อมสภาพอย่างชัดเจนของหินบะซอลต์ ชนิดและพันธะยึดติดของวัสดุเชื่อมประสานเป็นปัจจัยสำคัญที่ควบคุมการสึกกร่อนหินทรายที่ถูกนำมาทดสอบ น้ำและกรดมีผลกระทบอย่างมีนัยสำคัญต่อการสึกกร่อนของหินแกรนิต

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PHONGSAKORN TORSANGTHAM : SLAKE DURABILITY INDEX TESTS OF THIRTEEN ROCK TYPES UNDER DRY, WET AND ACIDIC CONDITIONS. THESIS ADVISOR : PROF. KITTITEP FUENKAJORN, Ph.D., P.E., 101 PP.

WEATHERING/DEGRADATION/ACID/DECORATING STONE

Slake durability index tests have been performed up to 100 cycles in an attempt to assess long-term durability of thirteen rock types, divided here into four groups: basalt, carbonate, sandstone and granite groups. This long-term test is intended to distinguish the degradation rates of the tested rocks with similar strengths. Three series of the slaking cycles are performed under dry, wet and acidic conditions. The results indicate that degradation of carbonate rocks, particularly travertine, significantly increase when they subject to water and acid. Ferrous oxide contents, amount of vesicles and pore spaces clearly accelerate the degradation rate of the tested basaltic rocks. Types and cohesive bonding of the cementing materials are important factors controlling the durability of the tested sandstones. Water and acid have insignificant impact on the durability of the tested granites.

School of Geotechnology   Student's Signature ________

Academic Year 2018   Advisor's Signature ________

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Phongsakorn Torsangtham

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SYMBOLS AND ABBREVIATIONS

σ_B	=	Brazilian tensile strength
σ_c	=	Uniaxial compressive strength
A	=	Mass of over-dry specimens
B	=	Mass of saturate test specimens
C	=	Mass of drum
E	=	Elastic modulus of rock
I_d	=	Slake durability index test
I_{dn}	=	Slake durability index after n cycles
n	=	Number of cycles of slake durability index test
W_i	=	Mass of drum plus oven-dried specimen first cycles of slake durability index test
W_n	=	Mass of drum plus oven-dried specimen n cycles of slake durability index test

CHAPTER I

INTRODUCTION

1.1 Background and Rationale

In geotechnical investigations involved with surface and subsurface structures, the evaluation of strength and deformability of intact rock and rock mass is frequently needed. These measurements become more difficult if the rocks encountered are influenced by weathering process. Most engineering works are confined to shallow depths where weathering has a dominant role to play and affects almost all the properties of rocks (Gupta and Seshagiri, 2000).

Several research efforts have been carried out in an attempt at identifying the impacts of weathering processes on the physical, hydraulic and mechanical properties of weak to medium strong rocks (Chigira and Oyama, 1999; Gupta and Seshagiri, 2000; Kasim and Shakoor, 1996; Tugrul, 2004). The slake durability index test method of determining the rock durability has been standardized by the ASTM. The standard method is however conducted by using only two test cycles under wet condition. This may not be sufficient to distinguish some rocks with similar strength and compositions, and in particularly to determine their long-term durability. Rare attempt has been made to determine the relationship between the mechanical properties and mineral composition with the long-term rock durability. This knowledge would be useful to predict the rock degradation of the construction and decorating stones in Thailand to ensure their long-term stability.

1.2 Research Objectives

The objective of this study is to investigate the long-term durability of thirteen construction and decorating stones commonly used in Thailand. Slake durability index test has been performed under dry, wet and acidic conditions. Up to 100 cycles will be conducted for each rock type. The water absorption is investigated before and after performing the slake durability index test. Petrographic thin section method analyzes and X-ray diffraction technique (XRD) will be also conducted to correlate mineral compositions with the specimen durability.

1.3 Research Methodology

The research methodology (Figure 1.1) is divided into 9 steps, including literature review, sample collection and preparation, slake durability index test (dry, wet and acidic conditions), water absorption, petrographic techniques, X-ray diffraction, result analysis, discussions, conclusions and thesis writing.

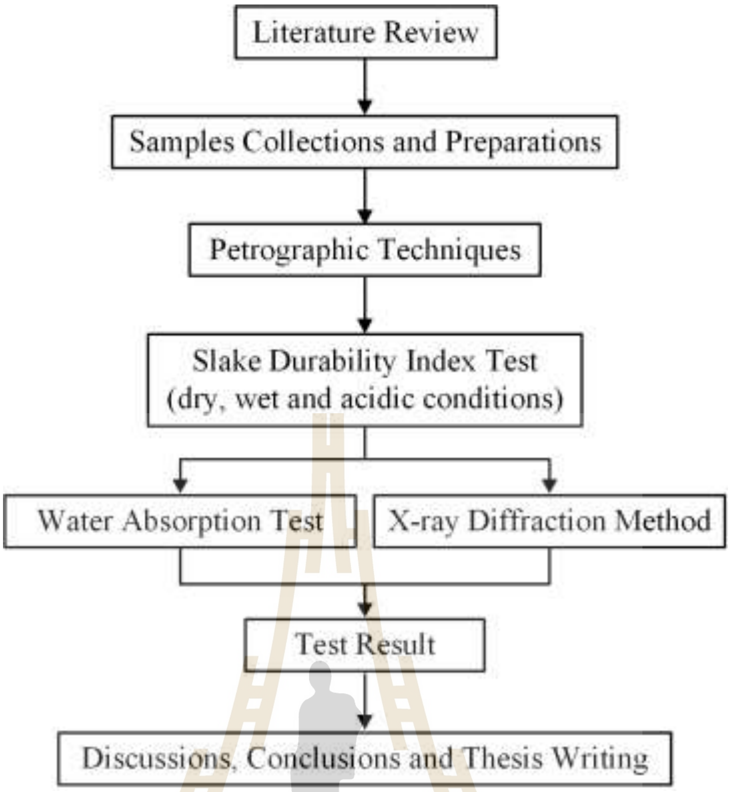


Figure 1.1 Research methodology.

Task 1: Literature review Literature review is carried out to improve an understanding of weathering process and factors affecting durability of rocks. The reviewed topics include weathering process effect to rock durability and factor affecting rock durability some rocks (mineral composition and physical properties factors environment). The sources of information are from journals, technical reports and conference papers.

Task 2: Samples collection and preparation Thirteen rock samples encountered in Thailand are used in this study. Sample preparation is carried out in the laboratory at the Suranaree University of Technology. Preparation of these samples will follow the ASTM (D4644-07) standard practice.

Task 3: Petrographic analyses Petrographic analyses are carried out by using thin section method. The thin sections of 30 microns thickness of each rock type will be prepared and examined under a polarized light microscope from each kind samples before slake durability index testing. The result is useful for explanation the effect of texture, grain and crystal size, shape and packing of grains of each rock types on rock degradation.

Task 4: Slake durability index test Slake durability index test is performed under dry, wet and acidic conditions. The test procedure follows the ASTM D4644-07 standard practice, except that 100 cycles are undertaken rather than the two cycles specified by the standard the water absorption test, petrographic analyses and X-ray fluorescence are performed.

Task 5: Water absorption test Water absorption tests (ASTM C127-04) are performed to determine the bulk specific, apparent specific gravity and absorption of the rock specimens under various stages of weathering. The samples are investigated at initial condition and after 20, 40, 60, 80 and 100 cycles of slake durability index testing. The results are presented in term of the absorbed rate of rock specimen under various environmental conditions.

Task 6: X-ray diffraction (XRD) analysis The XRD analysis (Moore C., 1970) is performed on finely ground rock powder pressed into coherent pellets. The analysis will be performed before and after slake durability index test. The result can be used to identify the effect of weathering process on changing to mineral compositions which may affect rock stability.

Task 7: Test result The results obtained from the slake durability index test under dry, wet and acidic condition, petrographic examination and XRD analyses are compared to determine the mathematical relationship equation for use to predict the long-term rock stability.

Task 8: Discussions, conclusions and thesis writing Discussions are made on the reliability and adequacies of the approaches used here. Future research needs will be identified. All research activities, methods, and results are documented and complied in the thesis. The research or findings are published in the journal.

1.4 Scope and Limitations

The scope and limitations of this study include as follows:

1) Thirteen rock types will be collected from the field including

- Aphanitic basalt
- Vesicular basalt
- Ferrous oxide basalt
- Saraburi limestone
- Khao Khad marble
- Khao Khad travertine
- Pink granite
- White granite
- Phu Kradung sandstone
- Phra Wihan sandstone
- Sao Khua sandstone
- Phu Phan sandstone

2) Slake durability index test is conducted following ASTM D4644-07 standard practice.
3) Slake durability test is performed under dry, wet and acidic conditions up to 100 cycles.
4) Water absorption test follows ASTM C127-04 standard practice.
5) For the testing under acidic condition, an acid solution with pH=5.6 is prepared from concentrated sulfuric acid mixed with distilled water.
6) Mineral compositions are analyzed by using X-ray diffraction method and petrographic techniques.

1.5 Thesis contents

The first Chapter introduces the thesis by briefly describing the background of problems and significance of the study, and identifying the research objectives, methodology, scope and limitations. The second Chapter summarizes results of the literature review. Chapter three describes the rock sample collection and results of mineralogical analysis. Slake durability index testing and rock degradation simulation are presented in Chapter four. Chapter five shows the X-ray diffraction method relations between the weathering process and physical rock properties, as well as the prediction scheme of rock degradation. Chapter six provides the discussion, conclusions, and recommendations for future studies. Details of the laboratory experimental results are given in Appendix A.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the initial results of literature review carried out to improve an understanding of rock degradation by weathering process. The topics are reviewed here including the effect of weathering on rock durability, factors affecting rock durability (mineral composition factors, physical properties factors and environmental), and slake durability research results that affecting to the durability of some rocks.

2.2 Weathering Effect on Rock Durability

Weathering processes often are slow (hundreds to thousands of years). The amount of time that rocks and minerals have been exposed at the earth's surface will influence the degree to which they have weathered. Weathered material may be removed leaving a porous framework of individual grains, or new material may be precipitated in the pores, at grain boundaries or along fractures. Weathering processes can be divided into two types, chemical weathering due to chemical changes and physical or mechanical weathering as results of wind, temperature changes, freeze-thaw cycles, and erosion by streams and rivers. Chemical weathering is the breakdown of minerals into new compounds by the action of chemical agents, acid in air, in rain and in river water. Mechanical weathering is a process by which rock is broken into small fragments as a result of energy developed by physical forces. Examples are freeze-thaw cycles and temperature changes (Abramson et al., 1995).

Moon and Jayawardane (2004) indicate that an early loss of alkaline earth elements (magnesium, calcium and ferrous) can be measured geochemically before any significant mineralogical change occurs and is closely linked to a dramatic drop in the intact strength of slightly weathered basalt. This drop in intact strength in turn allows for fracture development in response to residual stresses, after which secondary mineral development occurs following well-established patterns.

In general, the mechanical weathering in volcanic rocks include that the surface tends to loosen easily and disintegrates at an early stage. The unlocking mechanism of volcanic glass may also be considered as a mechanical change. The dissolution of chemical components, such as ferric oxide and silica, which serve as intergranular cement, and volcanic glass may also commence at an early stage. Although the processes involved in both chemical dissolution and mechanical disintegration are difficult to measure, they may be the dominant weathering processes in these rocks, especially within the shallow portion of slopes affected by changes in the groundwater table. As a result of a water-glass reaction, some of the volcanic glass changes to clay minerals such as allophone and halloysite. The chemical changes mentioned above also accelerate the physical and mechanical changes that occur as results of small volumetric changes in intergranular structures. (Yokota and Iwamatsu, 1999)

In addition to some rock properties that are considered to be related to durability (such as natural moisture content, porosity, and mineralogy), several researchers use SDI as tool for assessing durability of soft rock in their efforts to determine the relation between it and engineering properties, strength, or degree of material weathering. (Koncagul and Santi, 1999; Oguchi and Matsukura, 2000; Oyama and Chigira, 1999; Gökceoğlu and Aksoy, 2000; Gökceoğlu et al., 2000; Tugrul, 2004; Ündül and Tuğrul, 2012)

2.3 Factors affecting rock durability

The durability of rock depends on grain size, shape, mineralogical maturity index and petrographic indices. Increased interlocking and strong cementing with reduced void tends to possess high densities, low porosity and offer good resistance against deformation. Therefore, the proportion of strong cement over total cement, void content, strong over weak contacts, grain-to-void contact and packing density are meaningful indices considering the rocks (Tamrakar et al., 2007; Gupta and Ahmed, 2007). The factors are clearly divided as follows:

2.3.1 Mineral compositions

The mineralogy and the geometric arrangement (microfabric) of particles affect slaking and strength of weak rocks. As a rock forming mineral, most of the correlations established by previous researchers (Fahy and Guccions, 1979; Gunsallus and Kulhawy, 1984; Shakoor and Bonelli, 1991) found a negative relationship between quartz content and uniaxial compressive strength of the investigated sandstones. Handlin and Hager (1957); Bell (1978); Tugrul and Zarif (1999); Yusof and Zabidi (2016) did not find any significant correlation and suggested that the structural interlocking of the quartz grains and not the quartz content itself influences uniaxial compressive strength. Also, while not clearly stated in the literature, it is believed that rocks composed of quartz grains should have a higher durability due to the higher resistance of this mineral to mechanical abrasion.

Bonding determines the ease with which microfractures can propagate through the specimen by disrupting the structure and breaking the bonds within the groundmass. Mineralogy of bonding between rock particles or cementing material is an important property that controls strength, hardness and durability. Quartz provides the strongest binding followed by calcite and ferrous minerals. Clay binding material is the weakest (Vutukuri et al., 1974). There is not much literature about the relationship between the mechanical properties of a rock and the cement and matrix content. Among published material, Bell (1978) reported that the strength increases proportionally with the amount of cement. Fahy and Guccione (1979); Shakoor and Bonelli (1991) state that the correlations they had found between cement and strength were insignificant.

2.3.2 Physical properties

Weathering processes cause important changes in rock porosity. Besides porosity, distribution of pore sizes is significant for the identification of changes of changes due to rock weathering and its effect on fabric (Tugrul, 2004). These factors are briefly discussed as follows.

Finer grained sediments are more susceptible to breakdown and at higher rates than coarse grained sedimentary materials (Andrews et al., 1980; Kolay and Kayabali, 2006; Gupta and Ahmed, 2007). Conversely, although there are conflicting findings, fine grained samples can withstand higher uniaxial compressive loads (Brace, 1961; Fahy and Guccions, 1979). The probable reason for this is the number of grain to grain contacts is higher for fine grained samples. Therefore, the applied external force is distributed over a larger contact surface.

Rocks made of rounded grains are more durable (Andrews et al., 1980) because crystals or grains with sharp edges are exposed to a greater degree of abrasion during the slake durability test, resulting in lower slake durability indices. Assuming properties such as mineralogy of grains and cement and degree of bonding are the same, a rock made of angular grains should be stronger and harder (due to better interlocking of grains) but less durable (due to higher degree of erosion) than a rock composed of rounded grains. Grain boundaries and type of grain contacts are likely to affect the strength of rock material (Ulusay et al., 1994; Shakoor and Bonelli, 1991). Since sutured contacts provide better interlocking of grains, these types of contacts should increase the hardness and durability of specimens also.

Bell (1978) correlates packing density, which is the space occupied by grains in a given area, with the uniaxial compressive and tensile strengths of Fell sandstone. He showed that strength increased with increasing packing density. Hoek (1965) suggests that severe interlocking of grains could occur in sedimentary rocks in which grains have been tightly packed and well cemented. This would result in a considerable increase in the amount of applied stress required to propagate grain boundary cracks. Shakoor and Bonelli (1991) did not find any significant relationship between packing density and strength.

While porosity determines the total surface area open to physical or chemical interaction, hydraulic conductivity determines the ease with which fluids can seep through these pores. A high value of hydraulic conductivity indicates a well interconnected pore network. The factors that affect hydraulic conductivity are mineral composition, texture, particle size distribution, characteristics of the wetting fluid, exchangeable cation composition, void ratio and degree of saturation of rock mass (Domenico and Schwartz, 1990). Clay rocks have a very high porosity but their permeability is in the order of 10-8 to 10-10 m/s. Clay minerals with granular or fibrous shape (Kaolinite and Illite) are permeable to a greater degree than those that are flake shaped (Montmorillonite). Strength, hardness and durability decrease with increasing water content. Therefore, it is not unreasonable to expect lower strength, hardness and durability values from specimens with relatively high hydraulic conductivity values, which should also have higher water content from experimental literature shows that the greater the water content, the lower the compressive strength of a specimen.

Moon (1993) concludes that groundmass microstructure is probably the most important factor controlling the geomechanical behavior of ignimbrites. Both strength and slake durability are controlled by closeness of packing of the groundmass (packing density), degree of bonding between individual grains and average crystal size.

2.3.3 Environmental condition

Mechanical and physical characteristics of rocks generally depend on their composition and texture because they are reflective of their environments during sedimentation, diagenesis and weathering in each location (Tamrakar et al., 2007). In general, water can soften the bonds or interact with mineral surfaces and alter their surface properties (Horn and Deere, 1962). With the aid of pore water pressure, it may cause instability along weakness planes. Water may also decrease frictional shearing resistance or change the characteristics of gouge or clay mineral constituents of the rock (Touloukian et al., 1981). Reduction in compressive strength due to water has been reported by numerous investigators including Kjaernsli and Sande (1963); lately by Moon (1993). High water content also decreases durability and hardness of rock specimens. Rocks containing non-swelling clay minerals, such as kaolinite, slake faster upon submersion in water when they are completely dry beforehand (due to pore air compression) (Moriwaki and Mitchell, 1977).

In urban or highly industrialized areas, other gases of an acidic nature are produced from combustion of fuels. In the case of sulfur component, sulfur trioxide dissolves in water to produce sulfuric acid (Charola, 1987). In Thailand have The Acid Deposition Monitoring Network in East Asia (EANET) state of acid deposition in country and the national measures implemented. Resulted monitoring of environment from 2010-2014, the rain is pH about 5.6 (Lee, 2016).

Gupta and Ahmed (2007); Ghobadi and Momeni (2011) has been observed that degradability of rocks is greatly influenced by their mineral constituents and texture in pH water. Rocks contain about rich in calcium carbonate and or magnesium carbonate are adversely affected in the acidic environment, whereas rocks rich in quartz, feldspar and muscovite are independent of pH of slaking fluid.

The resistance to weathering of rock depends on types of mineral present, surface area of rock exposed and porosity of rocks. Weathering is not only dependent on the mineral composition but also on the porosity of the rock (Robinson and Williams, 1994). Rocks consisting of coarse fragments such as granite easily weather physically but do not weather chemically fast. In contrast, in rock consisting of fine fragments, such as basalt, chemical weathering is quicker than physical weathering. The weathering of stratified sedimentary rocks is dependent on the orientation of the stratification and cementation. The ranking of some primary minerals in order of increasing stability is shown in Figure 2.1. Olivine weathers rapidly because the silicon tetrahedral is only held together by oxygen and the metal cations which form weak bonds. In contrast, quartz is very resistant, because it consists entirely of linked silicon tetrahedral. The rate of weathering is influenced by temperature, rate of water percolation and oxidation status of the weathering zone. Weathering depends on climate such as temperature and the mean annual precipitation rates. The mean lifetime of one millimeter of different rocks into a kaolinitic saprolite is shown in Table 2.1. These numbers suggest that in cold or tropical humid zone, the climate controls the rate of weathering.

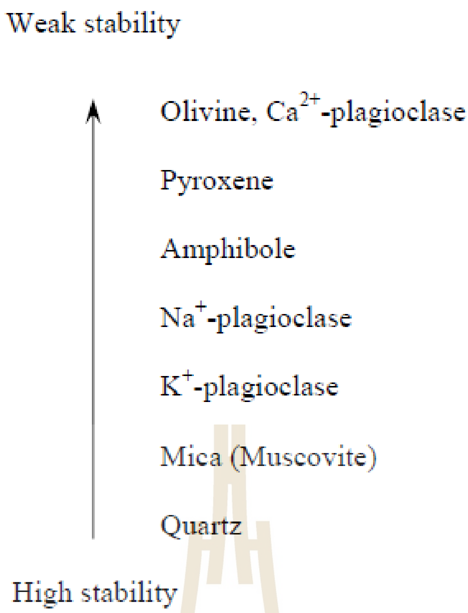


Figure 2.1 Stability of some primary minerals (Robinson and Williams, 1994).

Table 2.1 Mean lifetime of one millimeter of fresh rock (Nahon, 1991).

Rock Type	**Climate**	**Lifetime (years)**
Acid rocks	Tropical semi-arid	65 to 200
	Tropical humid	20 to 70
	Temperate humid	41 to 250
	Cold humid	35
Metamorphic rocks	Temperate humid	33
Basic rocks	Temperate humid	68
	Tropical humid	40

2.4 Slake Durability Research Results

The slake durability index is a measure of the durability of the rock when exposed to a slaking fluid medium. The variations in the slake durability indices of iron ore samples are studied by exposing them to acidic solutions of different pH values. The results indicate that the slake durability of iron ore rocks decrease with increase in the acidity of the solutions to which they are exposed. This behavior is attributed to combined forces of weathering and corrosion acting on iron ore in acidic slaking media (Singh et al., 2001). Rocks rich in calcium carbonate and magnesium carbonate are adversely affected in the acidic environment. Whereas, the rocks rich in quartz, felspar and muscovite are independent of the pH of the slaking fluid, which in turn, is more influenced by the texture of the constituent minerals (Gupta and Ahmed, 2007). Furthermore, many researchers indicate that decreasing the slake durability is associated with an increasing the clay content (Dick and Shakoor, 1992; Cetin et al., 2000; Lashkaripour and Ghafoori, 2003).

Sri-in and Fuenkajorn (2007) and Fuenkajorn (2005) study the series of slake durability tests, point load strength index tests, tilt tests and x-ray diffraction analyses on thirteen rock types, in an attempt at correlating the rock durability with its strength and mineral compositions. A concept was proposed to describe the rock degradation characteristics under the slake durability test cycles. A new classification system was also introduced for rock durability, which allowed predicting the rock strength as affected by weathering process. Results indicated that Phra Wihan, siltstone, Phu Kradung sandstone and Khok Kruat sandstone are classified as low to very low durability rocks, primarily due to the kaolinite content. The point load strength index decreases as increasing the difference in slake durability indices obtained from adjacent cycles (ΔSDI). Basic friction angles of the smooth (saw-cut) surfaces of the rocks decrease as the rapid heating-cooling cycles increase.

Fuenkajorn and Sri-in (2009) describes the rock degradation characteristics from the results of slake durability test cycles. A new classification system is introduced for rock durability, which allows the prediction of the strength of a rock when it has been affected by the weathering process. The aim of the study was to predict the influence of the weathering process (simulated by wetting and drying and heating and cooling) on the durability and strength of the volcanic, metamorphic and sedimentary rocks outcropping in eastern Thailand.

Walsri et al. (2012) determine the slake durability index from large-scale and standard scale testing which are performed under dry and wet conditions. The large-scale test yields rock deterioration twice greater than the small-scale test, primarily due to the greater energy imposed on the rock fragments. The weight losses under wet condition are greater than under dry condition for sandstones. After 10 test cycles the water absorption values sandstones are reduced as the number of test cycles increases is show in Figure 2.2. This implies that before testing the outer matrix of the rock fragments are weathered more than the inner portion. As the test cycle increased the scrubbing process slowly removed the outer matrix and exposes the fresher inner matrix to the testing environment. The inner matrix is comparatively fresh and had lesser amounts of pore spaces as compared to the outer part is show in Figure 2.3. Rock degradation under the rapid cooling-heating cycles in the laboratory is about 18 times faster than under the field condition in the northeast of Thailand.

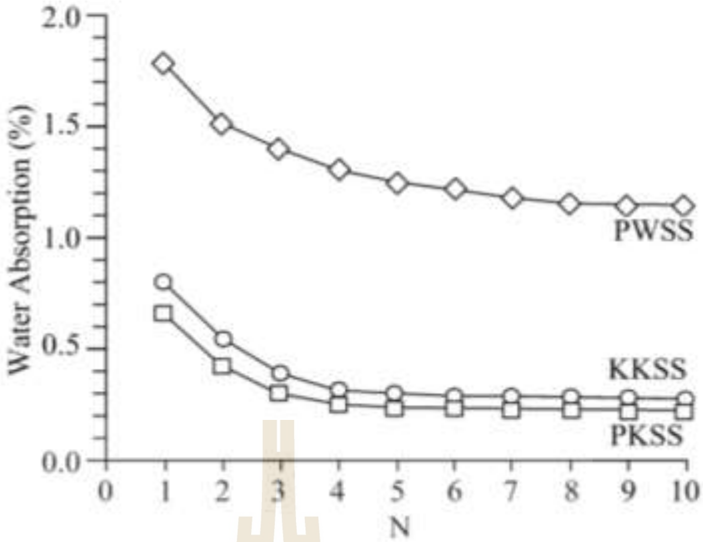


Figure 2.2 Water absorption as a function of test cycles (Walsri et al., 2012).

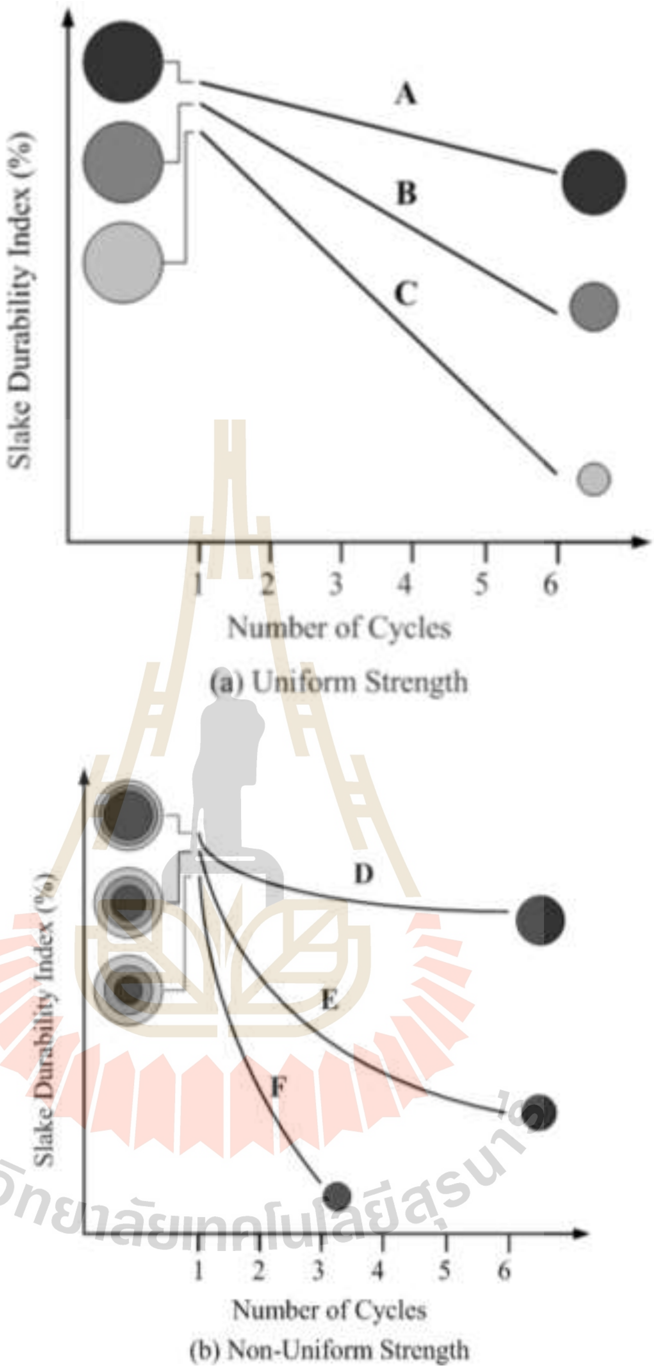


Figure 2.3 Proposed concept of rock degradation during SDI testing. Sample A, B and C (a) have uniform texture. Samples D, E and F (b) have weathered zone outside and fresher maxtrix inside. (Walsri et al., 2012).

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

Thirteen rock types were selected for this study. They were divided into four main groups: three basalt rocks, four carbonate rocks, four sandstone rocks and two granite rocks. These rocks represent the exposed outcrops that are commonly found in the central, northeast and west of Thailand. They also have significant impacts on long-term stability of many engineering structures constructed in the regions (e.g., embankments and foundations of highways, railways and reservoirs, dam abutments, and tunnels). The key criterion of sample selection is that the rock matrix should be as homogeneous as possible. This is to minimize the intrinsic variability of the test results. This chapter describes the mineral compositions of the rock samples, the locations from which they have been obtained and the mechanical properties of rock specimens are given in Table 3.1.

3.2 Sample collection

Table 3.2 gives rock names, locations from which they have been collected, and formations to which they belong. A map shown in Figure 3.1 gives the locations where the rock samples have been collected. For each location, a minimum of 5 kg of 1-1.5inch fragments have been collected to make 3 separate sets for testing. The rock fragments are planned for the slake durability tests.

Table 3.1 Mechanical properties of rock specimens.

Groups	Code	Density (g/cm^3)	Color	σ_c (MPa)	σ_B (MPa)	E (GPa)	Classification (ISRM, 1981)	Sources
Basalt	AB	2.79	very dark grey to black	188.1± 26.3	14.4±0.8	33.2±3.4	very strong	Kemthong and Fuenkajorn (2005)
	FB	2.71		170.2±68.8	13.7±1.7	-	very strong	This study
	VB	2.40		43.7±12.2	9.5±2.9	-	medium weak	This study
Carbonate	SB 1	2.73	dark gray	78.7±14.6	13.19±1.7	21.3±4.4	strong	Fuenkajorn (2005), Promma and Chitnarin (2015)
	SB 2	2.70	light gray	74.4±12.6	10.0±0.2	28.7±2.4	strong	Fuenkajorn (2005),
	T	2.58	yellowish brown	41.7	7.9±0.7	8.1±0.1	medium weak	Promma (2014), Khamrat et al. (2016)
	MB	2.73	white	50.5±1.6	8.0±0.3	13.1±5.7	strong	Fuenkajorn and Klanphumeesri (2011)
Sandstone	GST	2.55	grayish green	84.1±12.7	9.7	10.1±1.3	strong	Walsri et al. (2012), Phueakphum et al. (2013)
	YST	2.43	brownish yellow	86.3±11.1	10.7±0.7	11.1±0.9	strong	Fuenkajorn and Klanphumeesri (2011), Walsri et al. (2012)
	RST	2.37	red	67.5±4.6	9.4±1.8	11.5±0.5	strong	Fuenkajorn (2005)
	WST	2.36	brownish white	66.8±13.9	6.7	11.2±3.3	strong	Walsri et al. (2012), Phueakphum et al. (2013)
Granite	RGR	2.62	pink	138.1±18.9	15.0±3.6	34.5±4.3	very strong	Kemthong and Fuenkajorn (2005)
	GGR	2.62	white with scattered	119.3±18.3	11.3±1.5	32.4±4.6	very strong	Kemthong and Fuenkajorn (2005)

Table 3.2 Rock samples used in this study.

Rock Names	Code	Province	Rock Unit	Period	Reference
Basalt Group					
1.Aphanitic basalt	AB	Sila Chai mine, Buriram	Buriram Formation	Quaternary	Charusiri et al. (2004)
2.Ferrous basalt	FB	Sila Chai mine Buriram	Buriram Formation	Quaternary	Charusiri et al. (2004)
3.Vesicular basalt	VB	Sila Chai mine Buriram	Buriram Formation	Quaternary	Charusiri et al. (2004)
Carbonate Group					
4.Limestone1	SB1	Lopburi	Saraburi Group	Permian	Warren et al. (2014)
5.Limestone2	SB2	Lopburi	Saraburi Group	Permian	Chutakositkanon et al. (2000)
6.Khao Khad marble	MB	Saraburi	Saraburi Group	Permian	Dew et al. (2018)
7. Khao Khad travertine	T	Saraburi	Saraburi Group	Permian	Thambunya et al. (2007)
Sandstone Group					
8.Calcareous Lithic sandstone	GST	Nakhon Rachasima	Phu Kradung Formation	Jurassic	Racey et al. (1996)
9.Quartz sandstone	YST	Nakhon Rachasima	Phu Phan Formation	Cretaceous	Racey et al. (1996)
10.Arkosic Feldspathic sandstone	RST	Nakhon Rachasima province	Sao Khua Formation	Cretaceous	Racey et al. (1996)
11.White Quartz sandstone	WST	Nakhon Rachasima	Phra Wihan Formation	Cretaceous	Racey et al. (1996)
Granite Group					
12.White granite	GGR	Amphur Ban Tak, Tak	Tak Batholith	Carboniferous-Cretaceous	Mahawat et al. (1990)
13.Pink granite	RGR	Amphur Ban Tak, Tak	Tak Batholith	Carboniferous-Cretaceous	Mahawat et al. (1990)

Figure 3.1 Locations where rock samples have been collected.

Aphanitic basalt (AB), ferrous basalt (FE) and vesicular basalt (VB) are obtained from a quarry at Sila Chai mine in Muang district at Buriram province (Figure 3.2). The rocks in this area are of dense basalt zone with some of the scoria. volcanism took place during the Quaternary.

Limestones (SB1 and SB2) are obtained from borehole coring of Siam Tone Cooperation Limited in Lopburi province. The rocks are of Permian age.

Khao Khad marble (MB) and Khao Khad travertine (T) are obtained from the Thai Marble Cooperation Limited in Na Phra Lan district at Saraburi province. The rocks are of Permian age.

Calcareous lithic sandstone (GST), white quartz sandstone (WST), arkosic feldspathic sandstone (RST) and quartz sandstone (YST) are obtained from Subwai Congrete Cooperation Limited in Sikhio district in Nakhon Rachasima province. The rocks are of Jurassic to Cretaceous age.

White granite (GGR) and pink granite (RGR) are obtained from the Rungrung Sila Tak Granite Cooperation Limited in Ban Tak district at Tak province. The rocks are of Carboniferous age.

Figure 3.2 Basalt, ferrous basalt and vesicular basalt collected from Sila Chai mine in Buriram province.

3.3 Mineralogical Study

The mineral compositions of the rock samples are determined by using petrographic analysis. Tables 3.3 through 3.6 and Figure 3.3 through 3.32 give the results for basalt, carbonate, sandstone and granite rock types, respectively. The mineral compositions determined will be used as data basis to correlate and explain the degrees and characteristics of rock degradation which will be discussed in the following chapters.

Table 3.3 Mineral compositions of rock specimens in basalt rock types.

Basalt Rock Types	Density (g/cc)	Pyroxene (%)	Plagioclase (%)	Other (%)	Grain size (mm)	Color
1. Aphanitic basalt	2.79	50.0	50.0	-	0.5-2.0	black
2. Ferrous oxide basalt	2.71	66.0	34.0	-	0.5-1.5	black
3. Vesicular basalt	2.40	43.0	48.0	9.0	0.3-1.0	black

Table 3.4 Mineral compositions of rock specimens in carbonate rock types.

Carbonate Rock Types	Density (g/cc)	Calcite (%)	Dolomite (%)	Quartz (%)	Other (%)	Grain size (mm)	Color
1. Limestone 1	2.73	98.4	0.3	0.3	1.0	0.1-0.5	dark gray
2. Limestone 2	2.70	95.1	2.2	1.3	1.5	1.0-2.0	light gray
3. Khao Khad marble	2.73	100.0	-	-	-	0.5-2.0	white
4. Khao Khad travertine	2.58	98.7	0.1	0.2	0.9	0.3-1.0	yellow brown

Table 3.5 Mineral compositions of rock specimens in sandstone rock types.

Sandstone Rock Types	Density (g/cc)	Quartz (%)	Feldspar (%)	Albite (%)	Kaolinite (%)	Mica (%)	Other (%)	Cementing	Grain size (mm)	Grain sharp	Color
1. Calcareous lithic sandstone	2.55	48.8	-	46.1	5.1	-	-	calcium carbonate	<1.0	tabular	grayish green
2. Quartz sandstone	2.43	72.0	20.0	-	-	3.0	5.0	silica	0.1-0.2	angular	brownish yell
3. Arkosic feldspathic sandstone	2.37	57.0	2.9	39.5	-	0.6	-	hematite	0.1-0.2	angular	red
4. White quartz sandstone	2.36	75.0	15.0	-	-	7.0	3.0	hematite	0.1-0.4	angular	brownish white

Table 3.6 Mineral compositions of rock specimens in granite rock types.

Granite Rock Types	Density (g/cc)	Quartz (%)	Plagioclase (%)	Orthoclase (%)	Amphibole (%)	Other (%)	Grain size (mm)	Color
1. Pink granite	2.62	10.0	10.0	75.0	5.0	-	1.0-5.0	pink
2. White granite	2.62	30.0	40.0	5.0	-	5.0	2.0-5.0	white with scattered

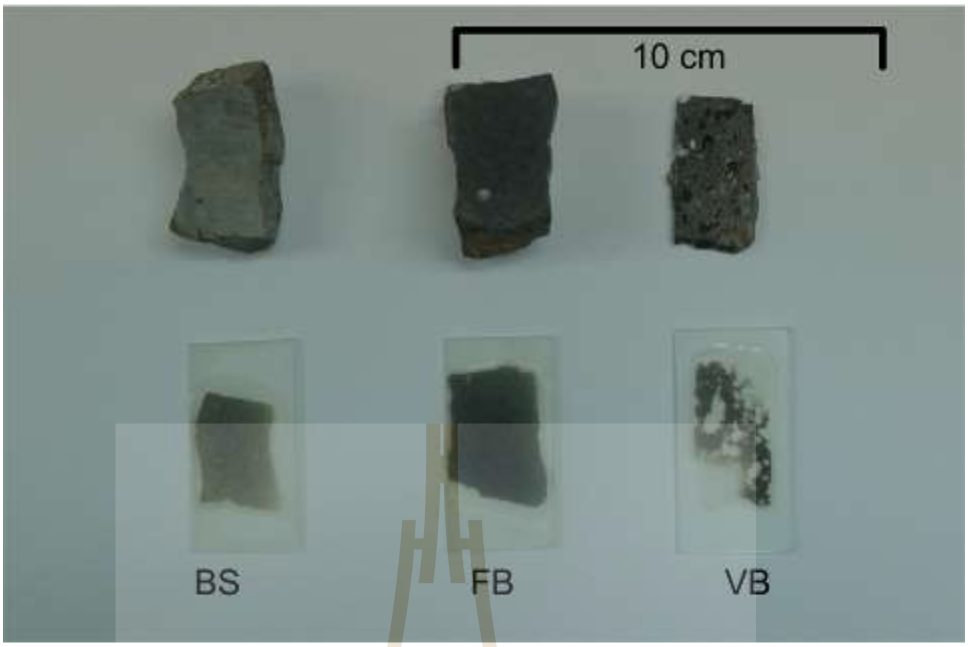


Figure 3.3 Hand specimens and thin sections of basalt group.

Figure 3.4 Hand specimens and thin sections of carbonate group.

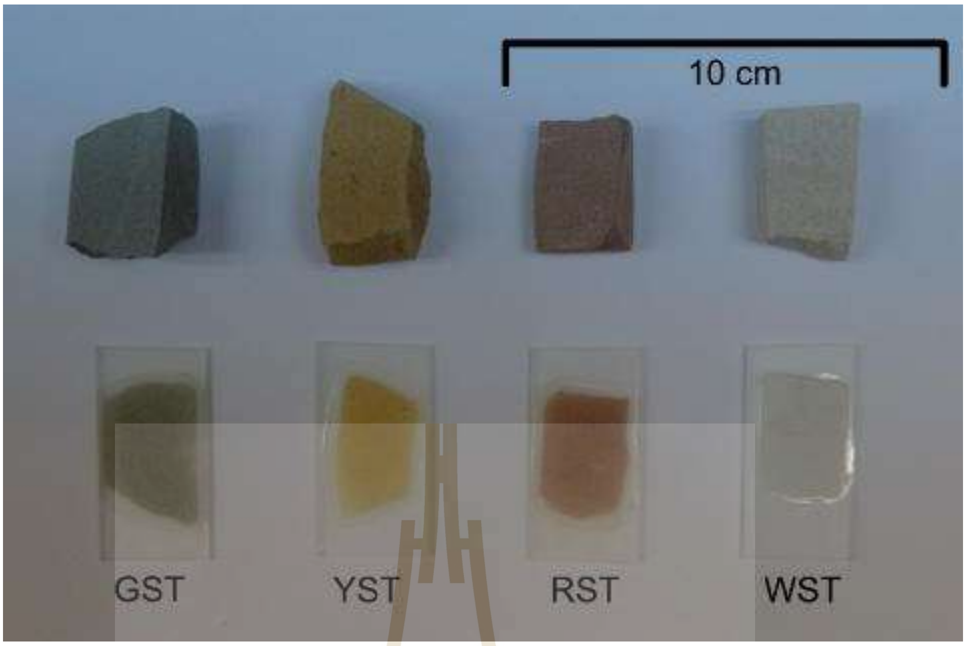


Figure 3.5 Hand specimens and thin sections of sandstone group.

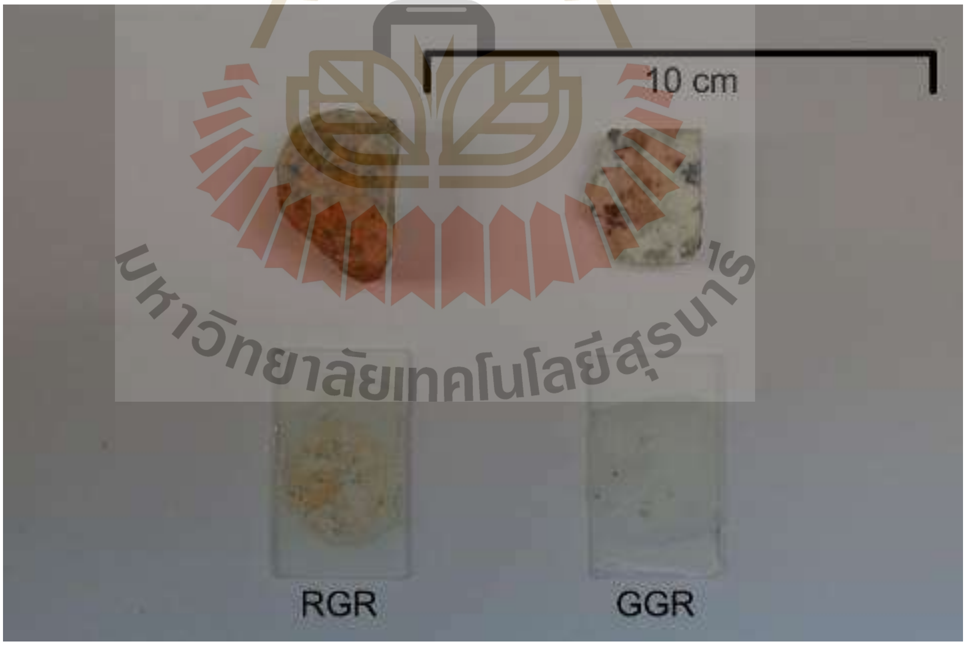


Figure 3.6 Hands specimen and thin sections of granite group.

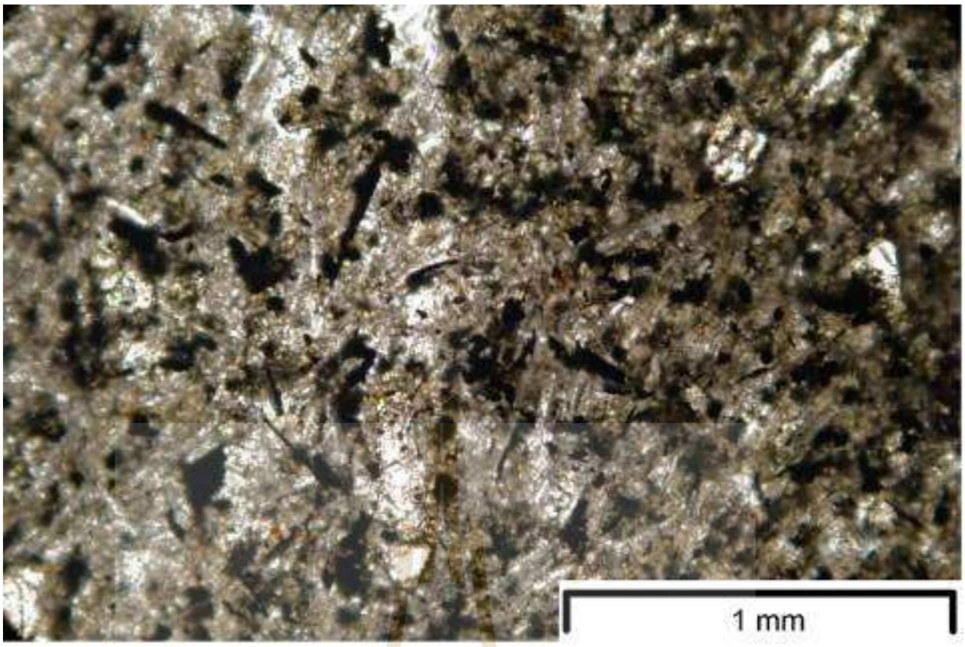


Figure 3.7 PPL-photomicrograph of the aphanitic basalt.

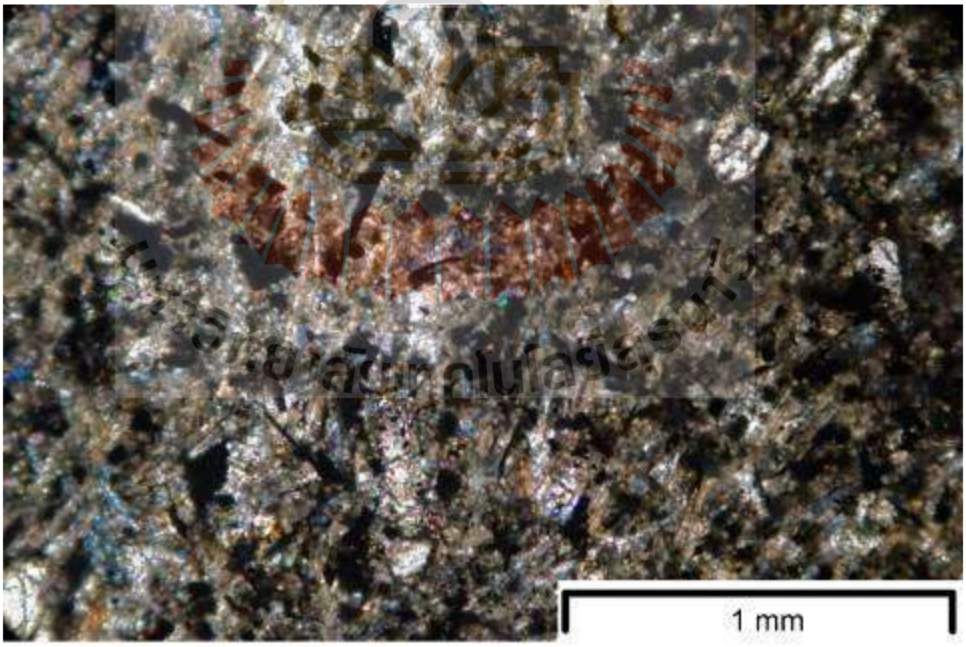


Figure 3.8 XPL-photomicrograph of the aphanitic basalt.

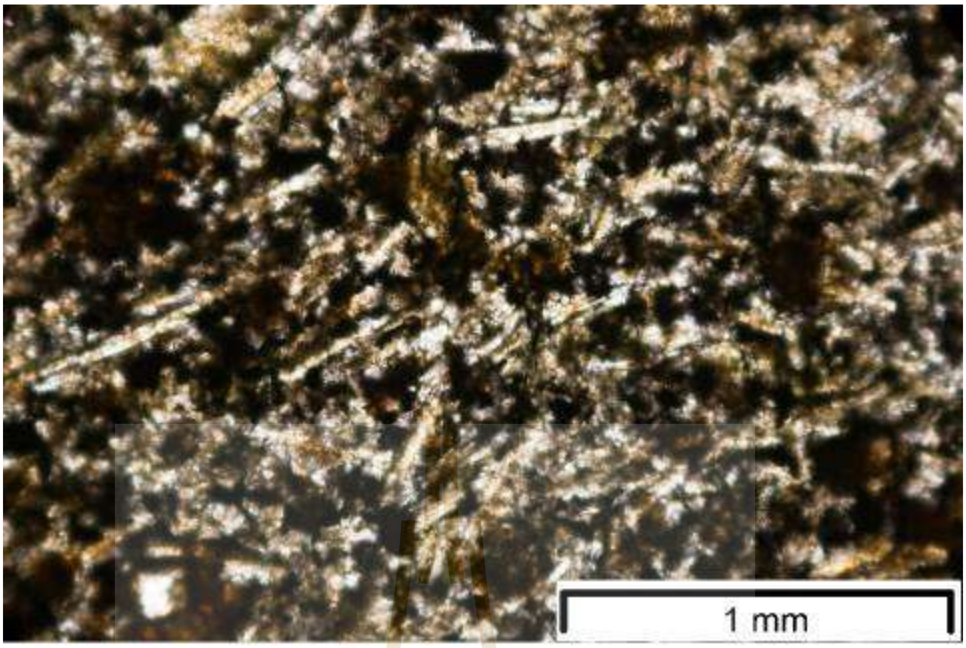


Figure 3.9 PPL-photomicrograph of the ferrous oxide basalt.

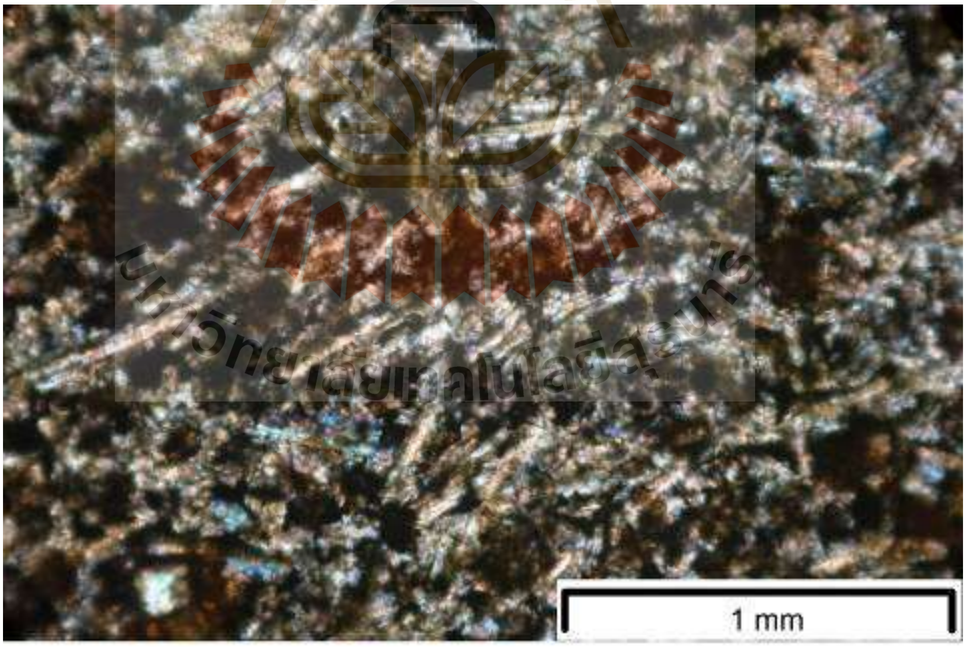


Figure 3.10 XPL-photomicrograph of the ferrous oxide basalt.

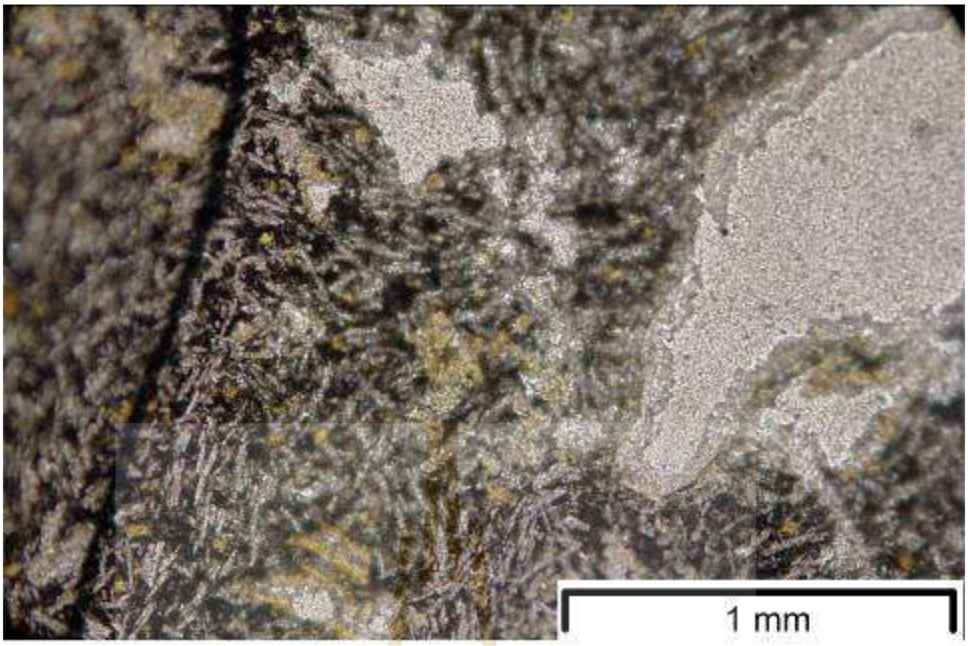


Figure 3.11 PPL-photomicrograph of the vesicular basalt.

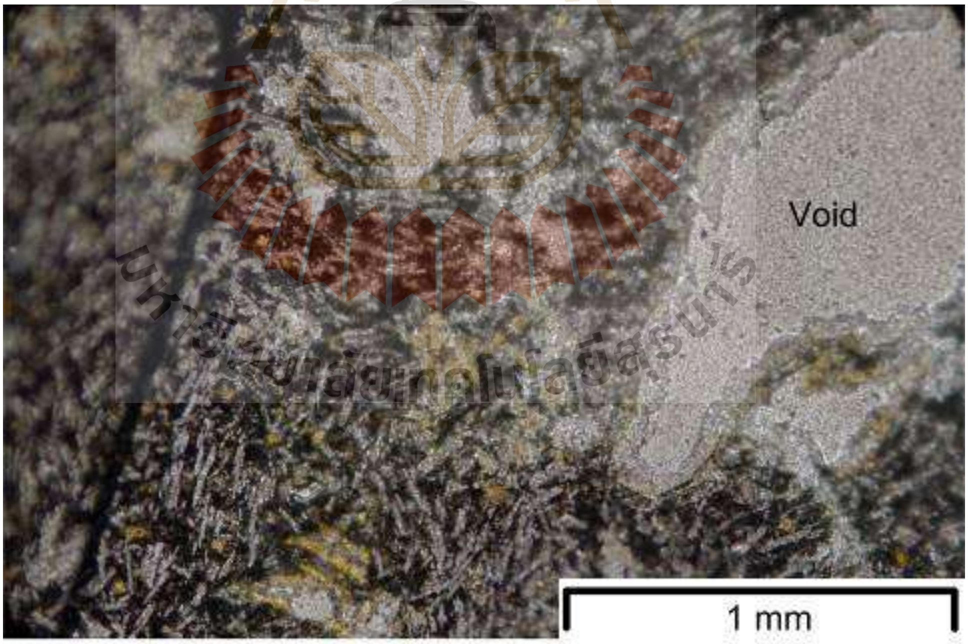


Figure 3.12 XPL-photomicrograph of the vesicular basalt.

Figure 3.13 PPL-photomicrograph of the limestone 1.

Figure 3.14 XPL-photomicrograph of the limestone 1.

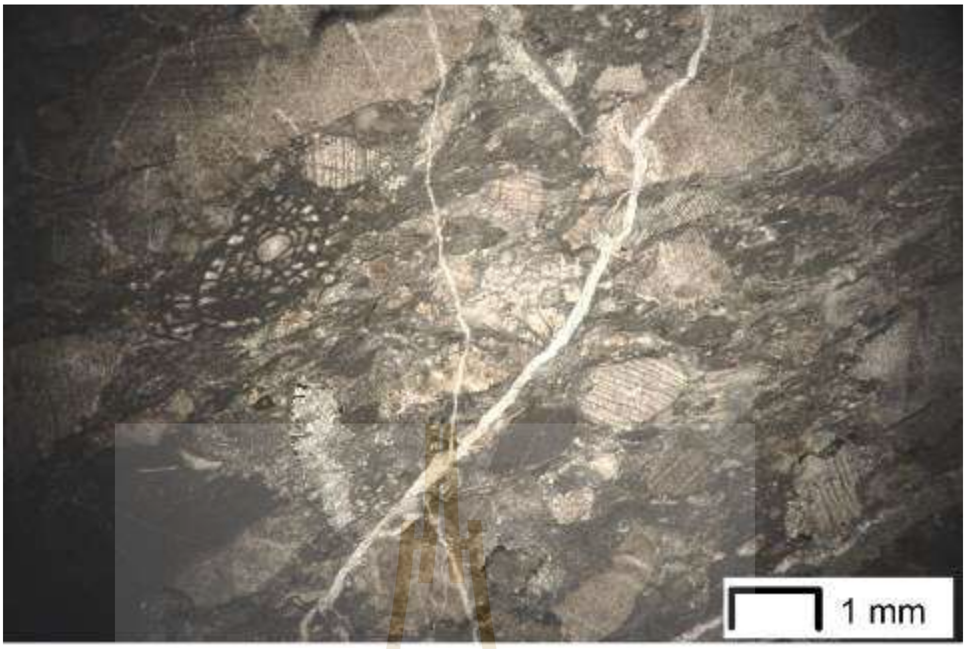


Figure 3.15 PPL-photomicrograph of the limestone 2.

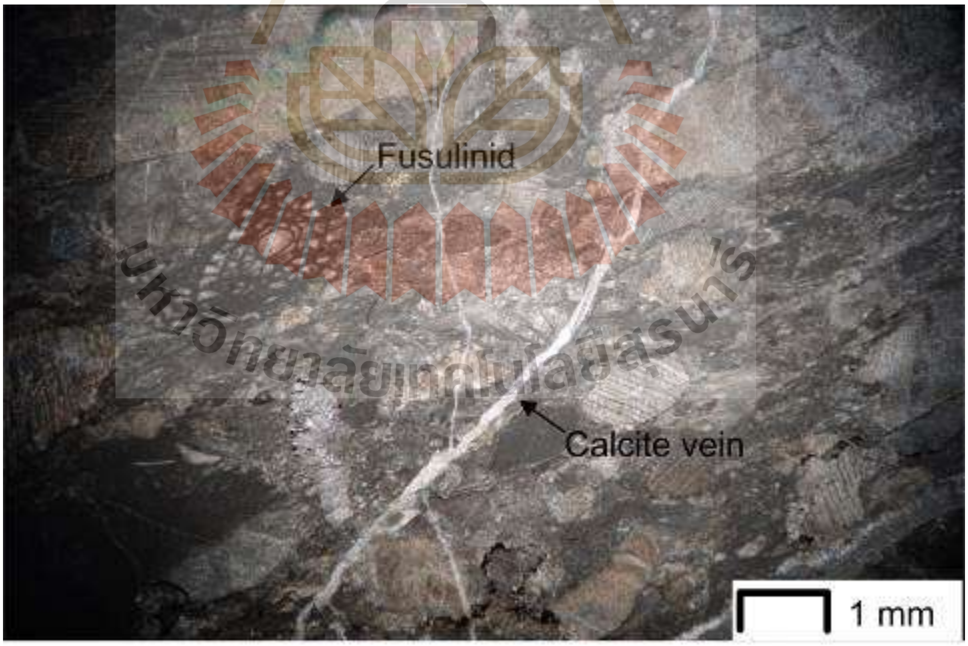


Figure 3.16 XPL-photomicrograph of the limestone 2.

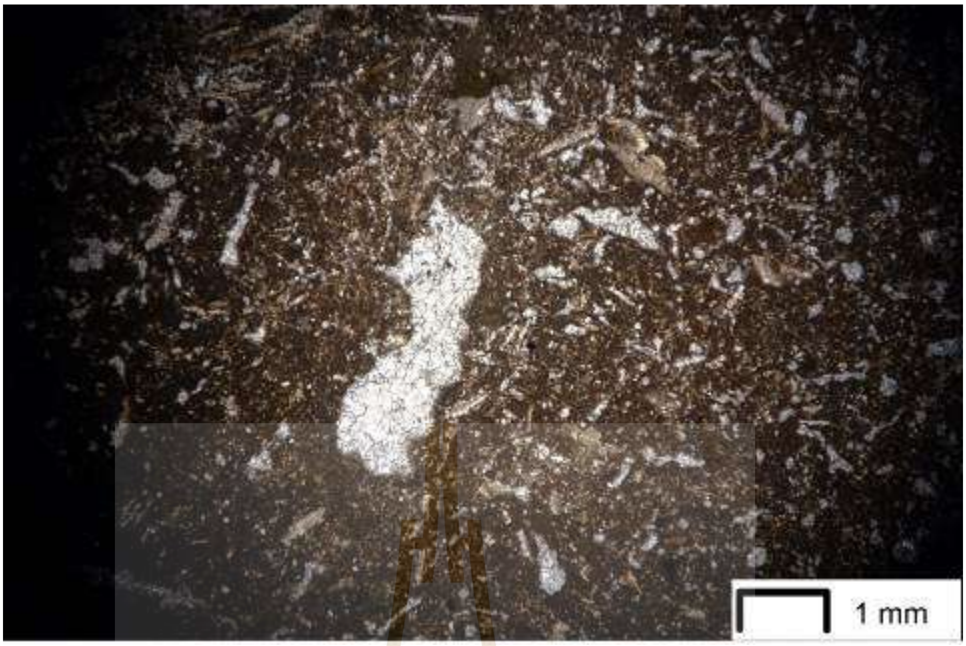


Figure 3.17 PPL-photomicrograph of the Khao Khad travertine.

Figure 3.18 XPL-photomicrograph of the Khao Khad travertine.

Figure 3.19 PPL-photomicrograph of the Khao Khad marble.

Figure 3.20 XPL-photomicrograph of the Khao Khad marble.

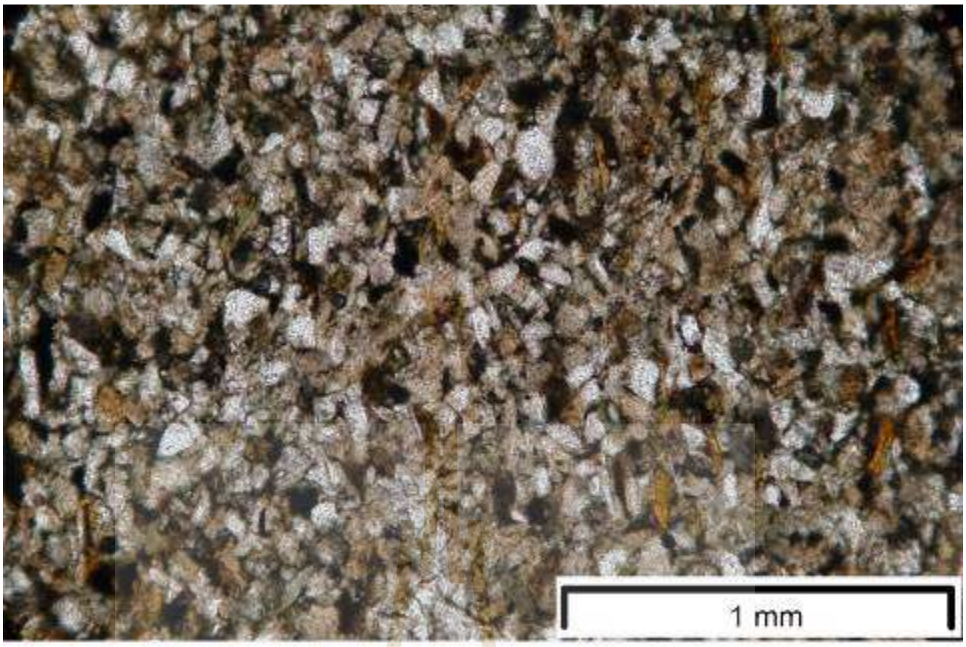


Figure 3.21 PPL-photomicrograph of the calcareous lithic sandstone.

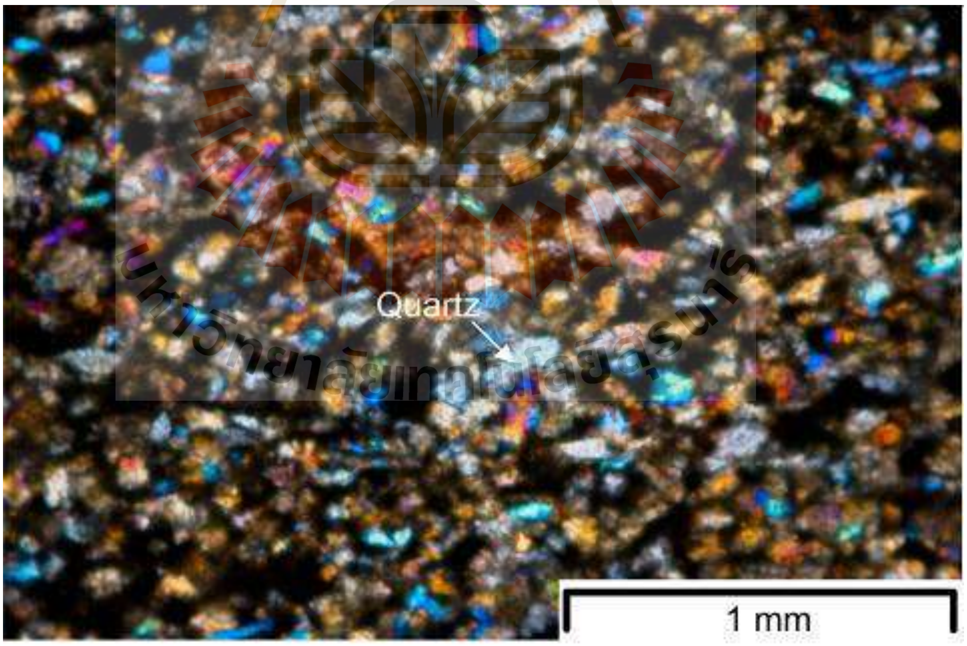


Figure 3.22 XPL-photomicrograph of the calcareous lithic sandstone.

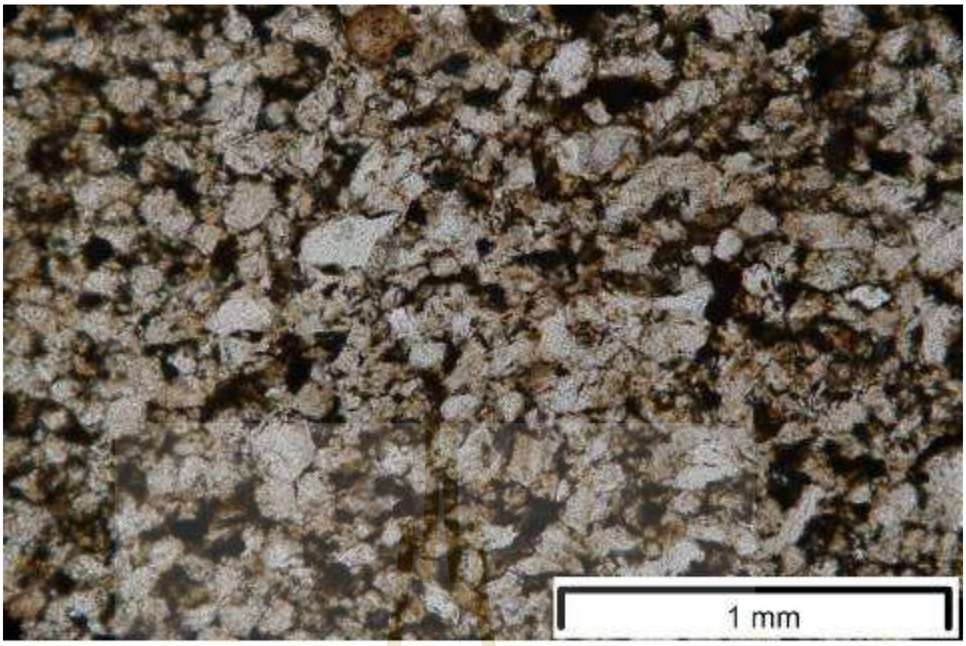


Figure 3.23 PPL-photomicrograph of the quartz sandstone.

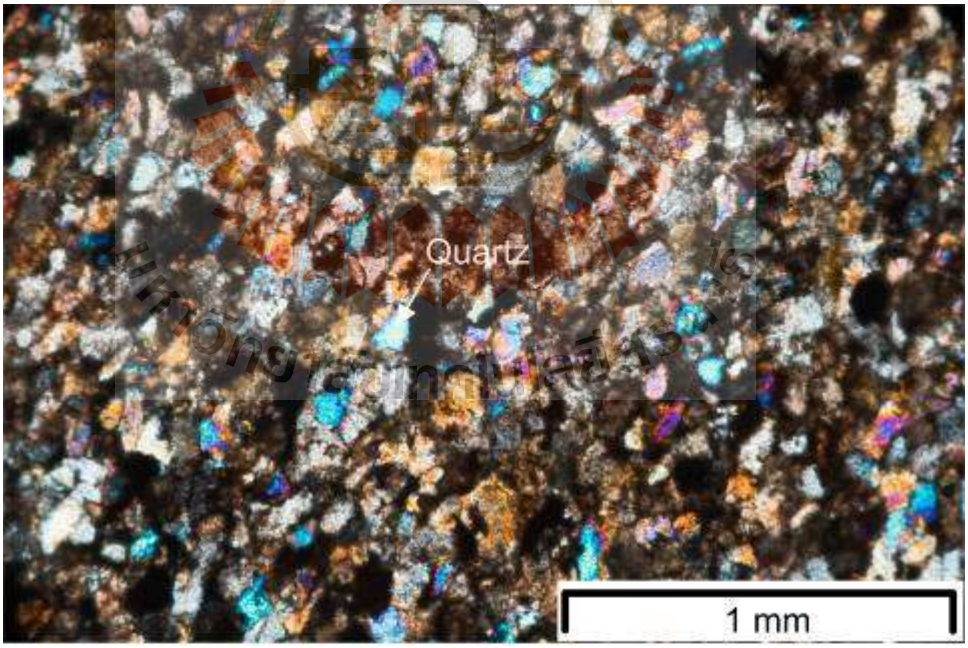


Figure 3.24 XPL-photomicrograph of the quartz sandstone.

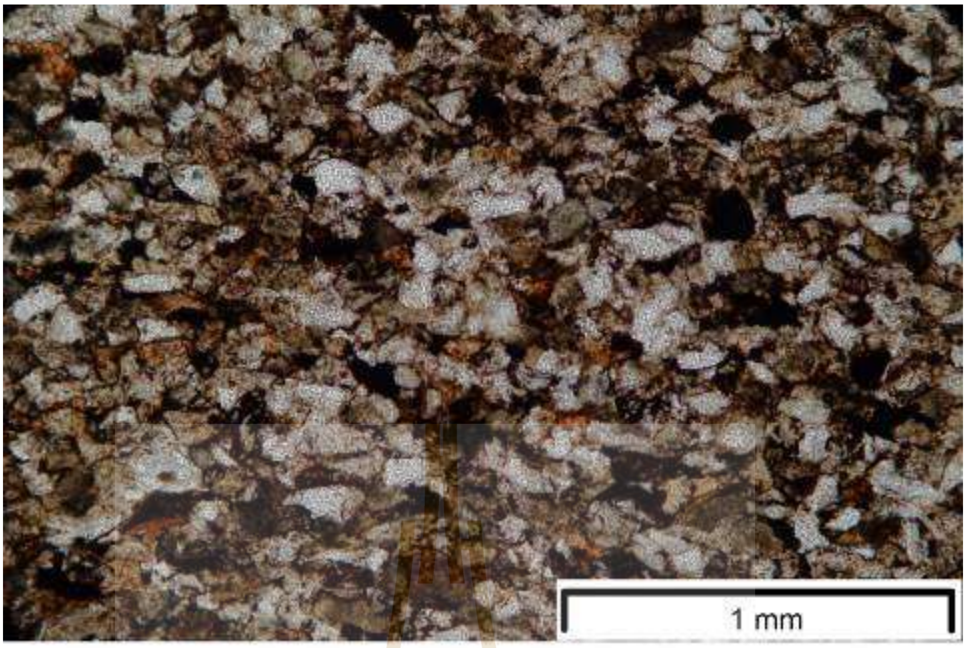


Figure 3.25 PPL-photomicrograph of the arkosic feldspathic sandstone.

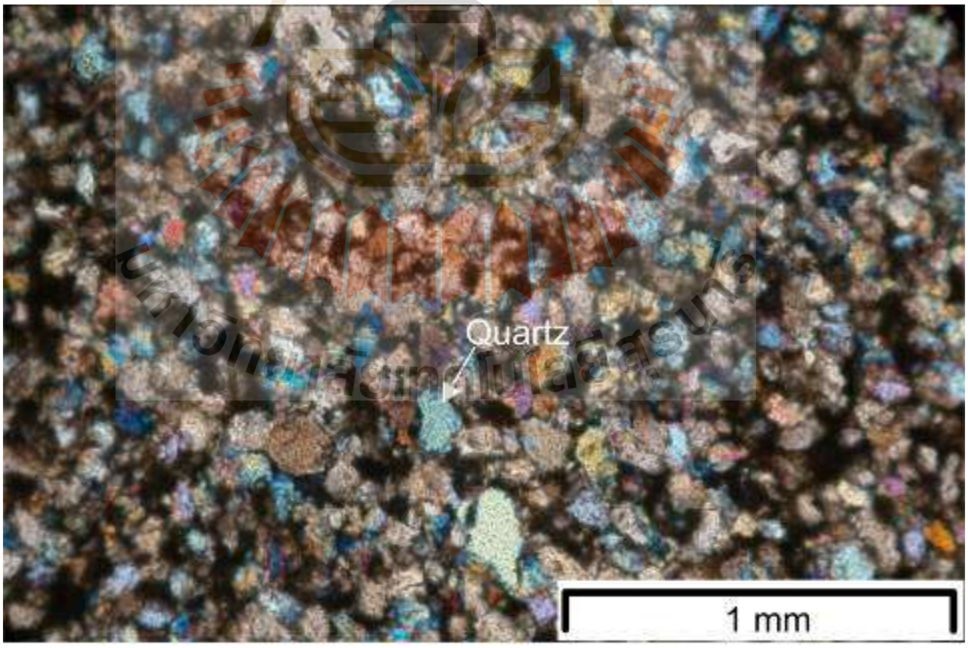


Figure 3.26 XPL-photomicrograph of the arkosic feldspathic sandstone.

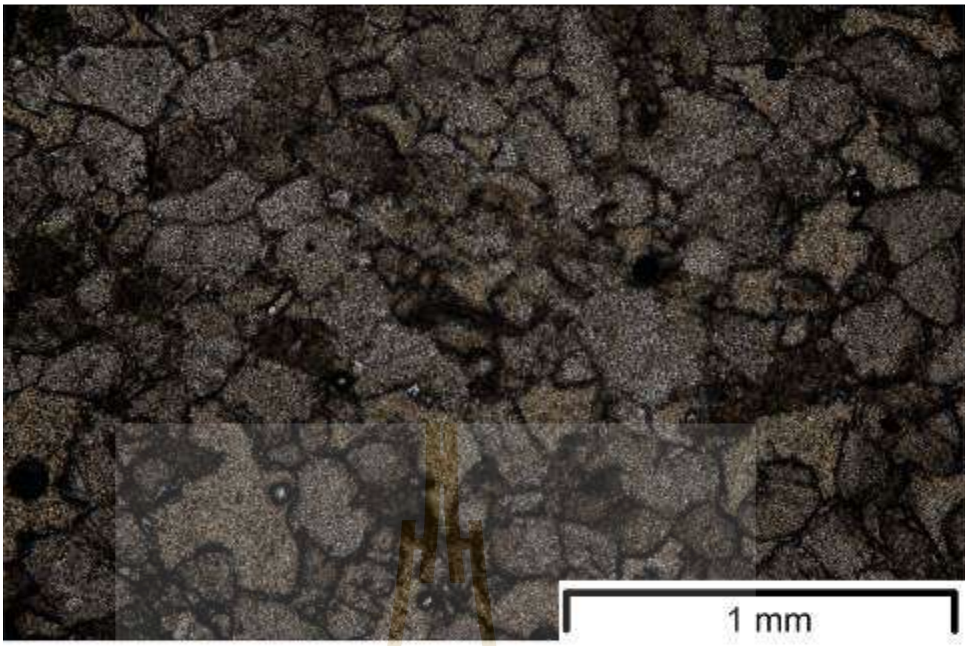


Figure 3.27 PPL-photomicrograph of the white quartz sandstone.

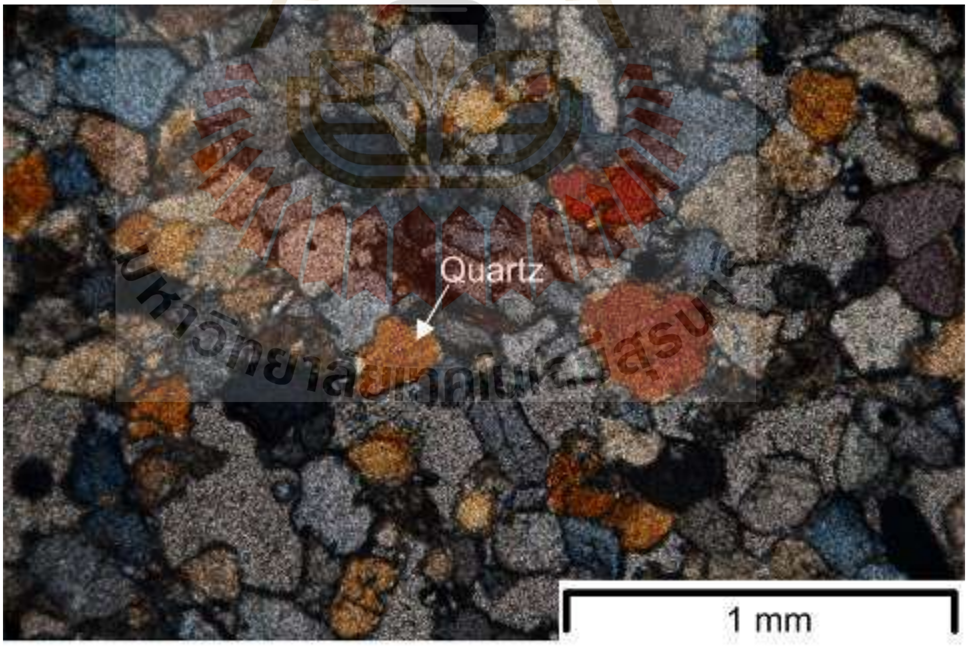


Figure 3.28 XPL-photomicrograph of the white quartz sandstone.

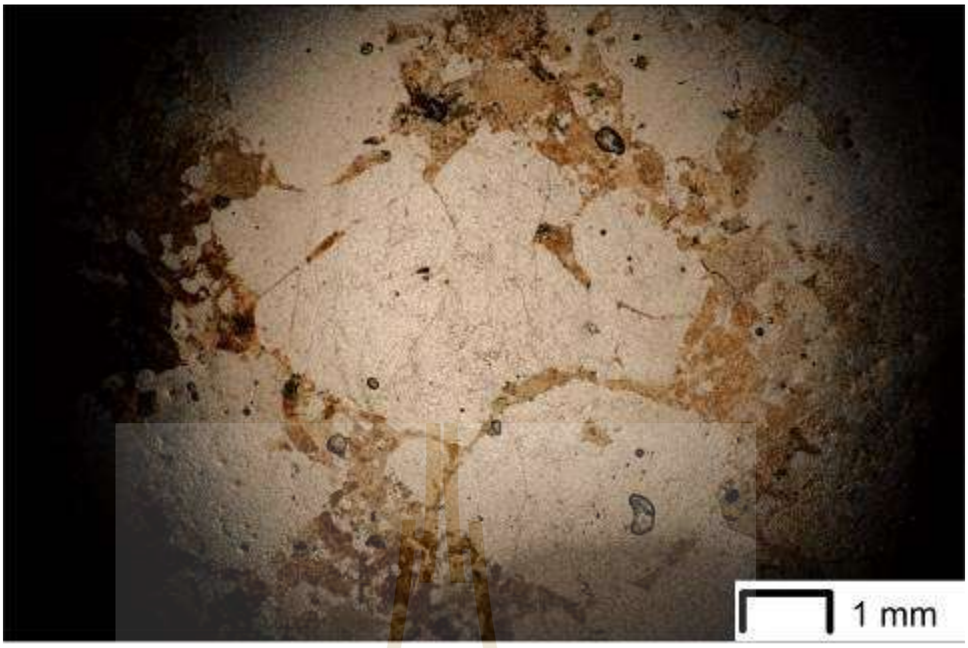


Figure 3.29 PPL-photomicrograph of the pink granite.

Figure 3.30 XPL-photomicrograph of the pink granite.

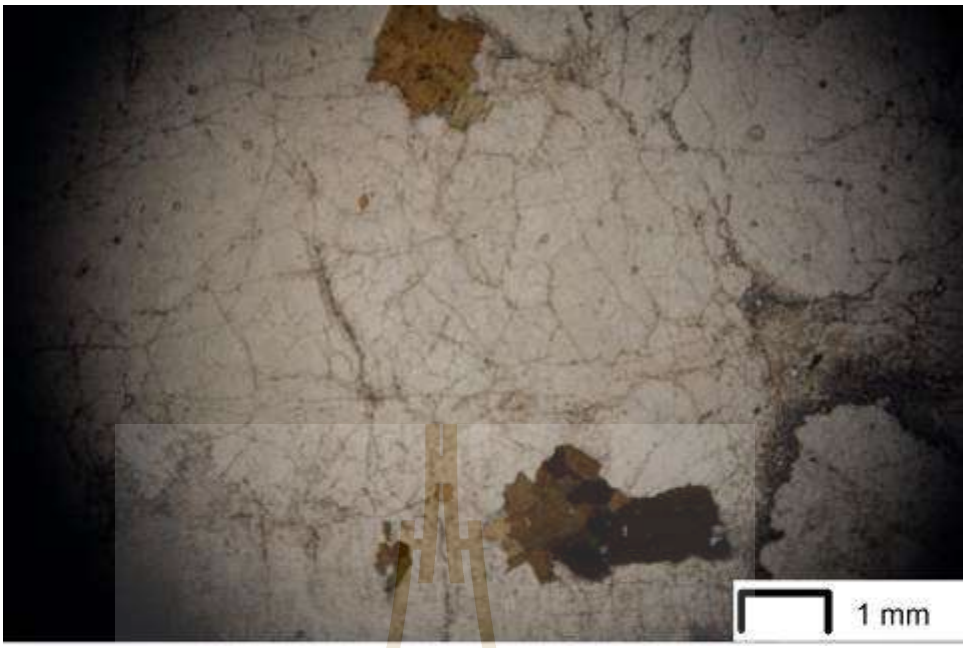


Figure 3.31 PPL-photomicrograph of the white granite.

Figure 3.32 XPL-photomicrograph of the white granite.

CHAPTER IV

SLAKE DURABILITY INDEX TEST

4.1 Introduction

The laboratory testing performed can be divided into two main types: slake durability index testing and water absorption testing. The absorption tests of rock degradation are performed every 20 cycles of slake durability index test. The results are used as indicators of the degrees of rock weathering.

4.2 Slake Durability Index Test

The primary objectives of the slake durability index test (hereafter called I_d test) are to determine long-term durability of the rock specimens, to establish weathering and degradation characteristics of each rock type, and to assess the impact of water and acid solution on the rock degradation. Three conditions of I_d test were performed on three separate sets of rock specimens with similar and comparable characteristics.

4.2.1. Sample collection

Three separate sets of specimens for each rock type have been prepared for testing under dry, wet and acidic conditions. For each test condition, the test specimens consist of ten representative, intact, roughly equidimensional fragments weighing 40 to 60 g (Table 4.1). These fragments are produced by braking with hammer. The total specimen weigh is between 450-550 g.

4.2.2. Test method

Figure 4.1 shows the slake durability test apparatus used in this study. The electronic device can control constant rotation rate of the drum at 20 rpm for a period of 10 minutes. The drum is made of 2.00 mm square-mesh. It is cylindrical in shape, with a diameter of 140 mm and a length of 100 mm. Three series of the slake durability index test are performed on three separate sets of rock specimens for each rock type. For the first series, the test procedure generally follows ASTM D4644 standard practice, except that 100 cycles are undertaken rather than the two cycles as specified by the standard. This is primarily to establish a longer trend of weight loss as the rocks continue subjecting to more cycles of scrubbing in the drum. A trough supports the drum in a horizontal manner such that the drum is partially submerged and free to rotate about its axis. The trough is capable of being filled with slaking fluid to 20 mm below the drum axis, and allowing at least 40 mm unobstructed clearance between the trough and the bottom of the mesh. The temperature of the water in the trough is 25 Celsius, following ASTM D4644 standard practice. The second test series is identical to the first one except that there is no water in the trough, i.e. slaking under dry condition. The third test series is carried out to assess the effect of sulfuric acid, which is the major constituent of acid rain, on the weathering process of rock under in-situ condition. This solution is prepared by pouring 2.5 cc of 1 M concentrated sulfuric acid solution into 1 liter of distilled water. A pH meter is used to measure the hydrogen-ion activity in the water-based solution to confirm the precise pH equal to 5.6. The solution fluid is filled to 20 mm below the drum axis in the trough, following ASTM standard practice.

For all test series, after removing the specimens from the drum, they are oven-dried for 12 hrs. These processes are repeated 100 times (100 days). The weight loss for each cycle is measured and used as an index of the durability of the test specimens. All calculations follow the ASTM D4644-07 standard practice.

The samples of thirteen rock types under three conditions were dried by oven which are also placed in the oven at 110 Celsius for 12 hours. The specimens were placed in air for 30 minutes. The mass of each samples at balance (sensitivity of balance = 0.01 g) is weight and recorded. After the slaking testing is completed, the samples are dried by oven again which is called one cycle. This procedure is shown in Table 4.2. The thirteen rock types are testing up to 100 cycles.

The slake durability index test can be determined for each set specimen under each condition using the following relation

$$I_{dn} = [(W_n-C)/(W_i-C)] \times 100 \qquad (4.1)$$

where I_{dn} is slake durability index after n cycles, W_n and W_i are mass of drum plus oven-dried specimen before the n and first slake durability index testing cycle, C is mass of drum, and n is a number of cycles of slake durability index test.

Table 4.1 Specimens before slake durability index test.

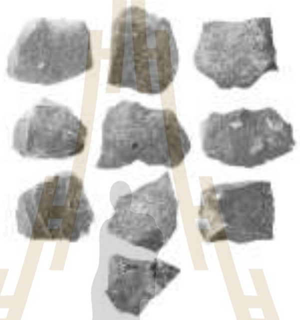
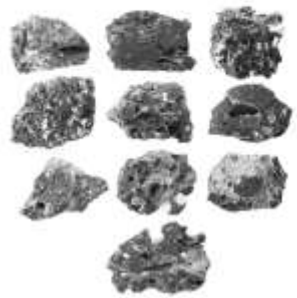
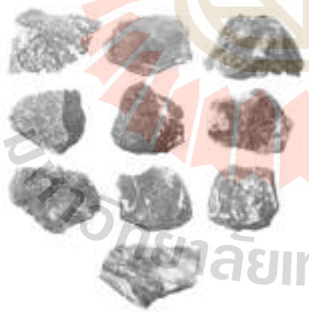
Groups	**Types of specimen for slake durability index test**			
Basalt				
	Aphanitic basalt (BS)	Ferrous basalt (FB)		Vesicular basalt (VB)
Carbonate				
	Limestone1 (L1)	Limestone2 (L2)	Khao Khad marble (MB)	Khao Khad travertine (T)

Table 4.1 Specimens before slake durability index test (continue).

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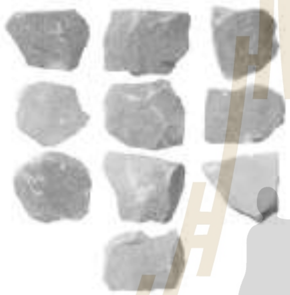
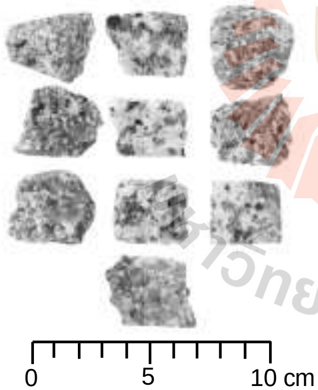
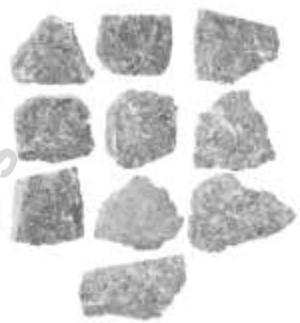
<tr><td rowspan="2">Sandstone</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Calcareous lithic sandstone (GST)</td><td>Quartz sandstone (YST)</td><td>Arkosic feldspathic sandstone (RST)</td><td>White quartz sandstone (WST)</td></tr>
<tr><td rowspan="2">Granite</td><td colspan="2">
</td><td colspan="2"></td></tr>
<tr><td colspan="2">White granite (GGR)</td><td colspan="2">Pink granite (RGR)</td></tr>
</table>

Figure 4.1 Slake durability index test apparatus.

Table 4.2 Slake durability index testing procedure.

Time (hours)	**Description**
0.5	Take the specimens off oven machine and cool down for 30 minutes
2	Weight and record the mass of each sample type
0.5	Prepare equipment and solution for slake durability index test
3	Slake durability index test
12	Be dried samples in oven machine

4.3 Water Absorption Test Method

The objective of the water absorption testing of rock degradation is to experimentally assess the degrees of rock weathering as it is subjected to the cyclic changes of temperatures and humidity. The wet, dry and acidic conditions of thirteen rock types are tested after slake durability index testing of 0, 20, 40, 60, 80 and 100 cycles. The test method follows ASTM (C127-04) standard practice. The samples are placed in an oven at 105 Celsius for 12 hours and submerged in a tank of water at 25 Celsius for 24 hours (Figure 4.2).

The percentage of water absorption determined for each set specimen each condition is determined using the following relations

$$\text{Absorption, \%} = [(B-A)/A] \times 100 \qquad (4.2)$$

where A is mass of over-dry specimens, and B is mass of saturate test specimens.

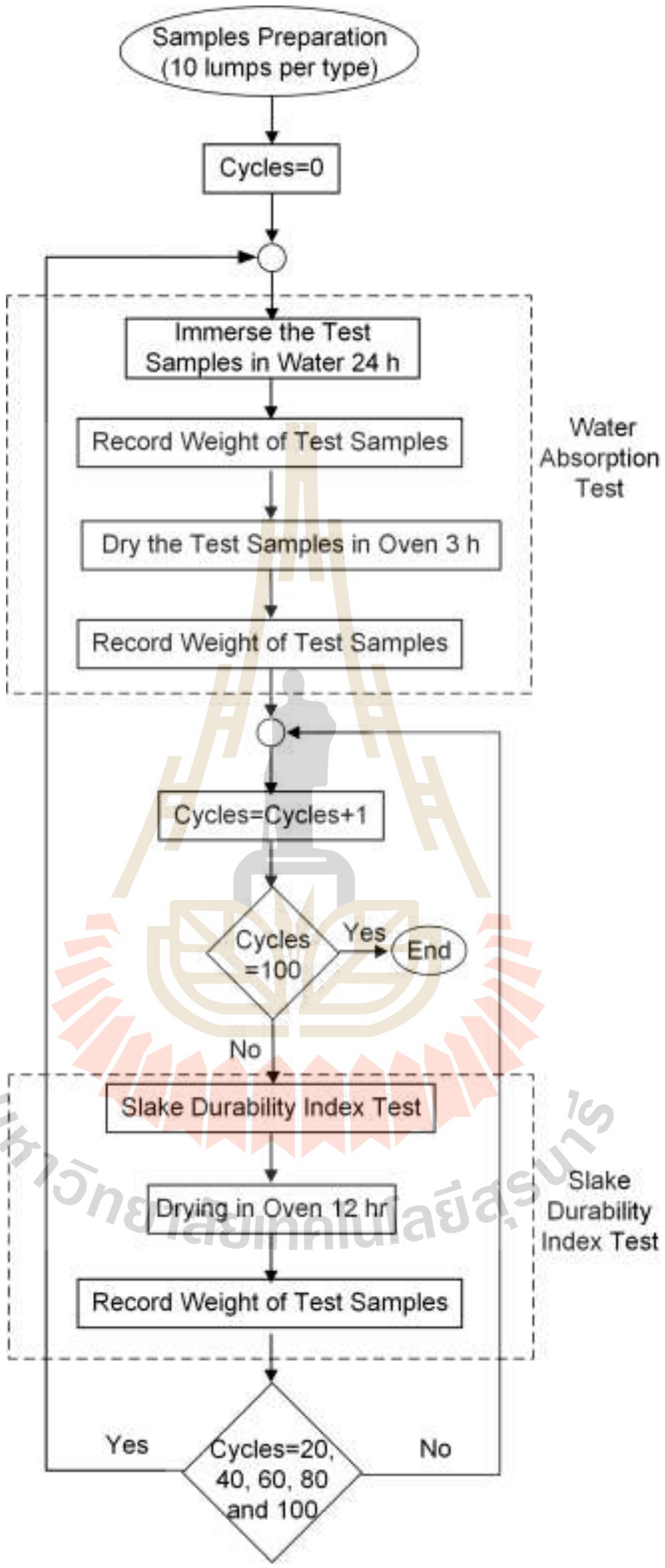


Figure 4.2 Procedure of water absorption test during slake durability index test for under dry, wet and acidic conditions.

CHAPTER V

TEST RESULTS

5.1 Introduction

This chapter describes the results of slake durability index tests under the three test conditions: dry, wet and acid. The water absorption measurements and post-test observations and also presented.

5.2 Slake Durability Index Test Result

The test results are plotted as a function of the number of cycles (N) for dry, wet and acidic conditions in Figures 5.1 through 5.4. The slake durability index of the specimens decrease under different conditions. Under two test cycles all rocks are considered as very high durability based on Gamble's classification. Testing up to 100 slake cycles can however distinguish the durability of these rocks. The most durable rocks seem to be the granite group. The igneous rocks (basalt and granite groups) can resist against wet and acidic environments while the carbonate groups and sandstone groups are sensitive to water and acid.

The degradation of the rocks in basalt group tends to be the same under dry, wet and acidic conditions (Figure 5.1). The vesicular basalt (VB), posing the lowest strength in the group (Table 3.1), degrades notably quicker than do the other two basalts for all test conditions. The results under dry condition indicate that the aphanitic basalt (AB), ferrous oxide basalt (FB) and vesicular basalt (VB) have I_d at 100 cycles of 94.7%, 92.3% and 84.1%, and under wet condition of 94.3%, 91.2% and 85.5%, and under acidic condition of 89.9%, 85.8% and 81.9%, respectively.

The acid solution greatly accelerates the degradation of all rocks in the carbonate group (Figure 5.2). The results under dry condition show that the limestone1 (SB1), limestone2 (SB2), Khao Khad marble (MB) and Khao Khad travertine (T) show I_d at 100 cycles of 95.1%, 94.1%, 87.8% and 92.1%, under wet condition of 94.1%, 92.8%, 87.8% and 85.9%, and under acidic condition of 92.2%, 89.4%, 80.5% and 76.8%, respectively. Travertine (T) is highly sensitive to water and acid, compared to the marble and limestone (Figure 5.2). Under dry condition, Khao Khad marble (MB) however degrades quicker than the other three carbonate rocks, but it is slightly more durable than travertine when both are under water and acid.

For rock specimens in the sandstone group, their degradations are varied under different test conditions. Figure 5.3 shows that under dry condition the calcareous lithic sandstone (GST), quartz sandstone (YST), arkosic feldspathic sandstone (RST) and white quartz sandstone (WST) have I_d values of 91.8%, 89.8%, 87.9% and 82.2%, under wet condition of 76.3%, 87.1%, 85.3% and 80.2%, under acidic condition of 68.9%, 84.2%, 80.4% and 77.8%, respectively. The calcareous lithic sandstone (GST), even though posing relatively high strength (Table 3.1), is highly sensitive to water and acid. It tends to be very durable under dry condition, but degrades quicker than other three sandstones under the fluids (Figure 5.3).

Both granites show very similar trends of degradation for dry, wet and acidic conditions, suggesting that water and acid have insignificance impact on their durability. They are classified as very high strength rock (Table 3.1). The pink granite

(RGR) is slightly more durable than the white granite (GGR) for all test conditions. The pink granite (RGR) and white granite (GGR) have I_d at 100 cycles of 96.8%and 95.1%, under dry conditions. Their durability in slightly lower under water and acid.

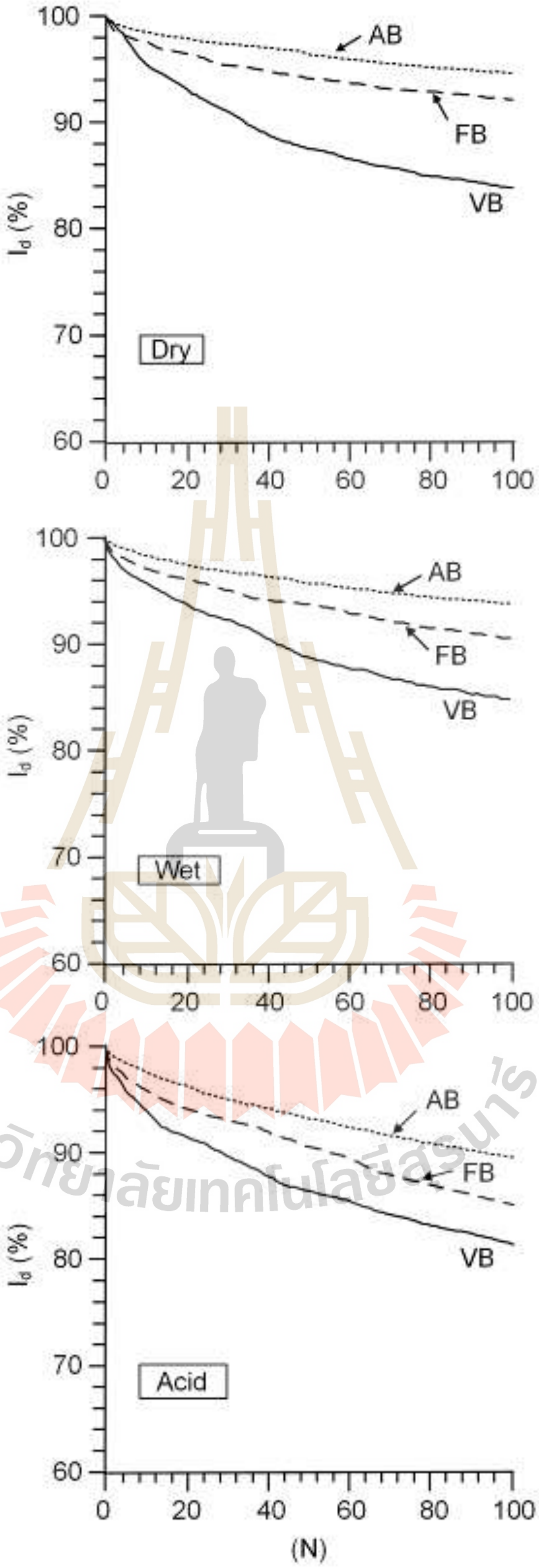


Figure 5.1 Slake durability index as a function of test cycle for basalt group.

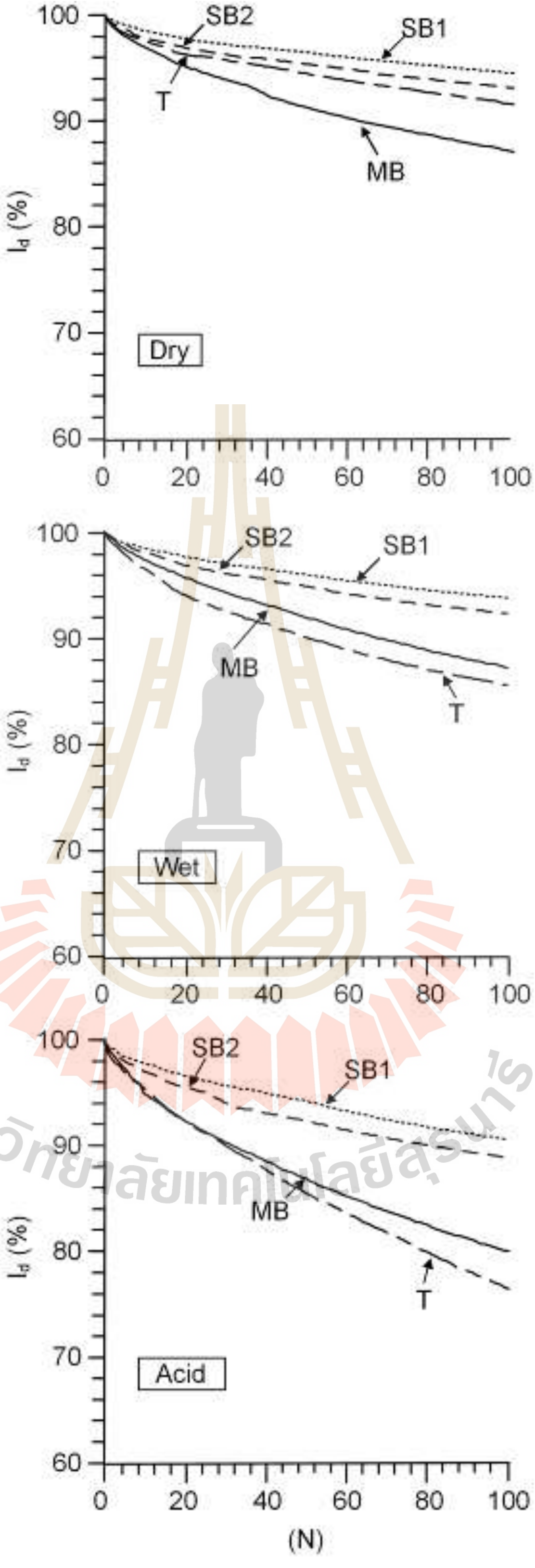


Figure 5.2 Slake durability index as a function of test cycle for carbonate group.

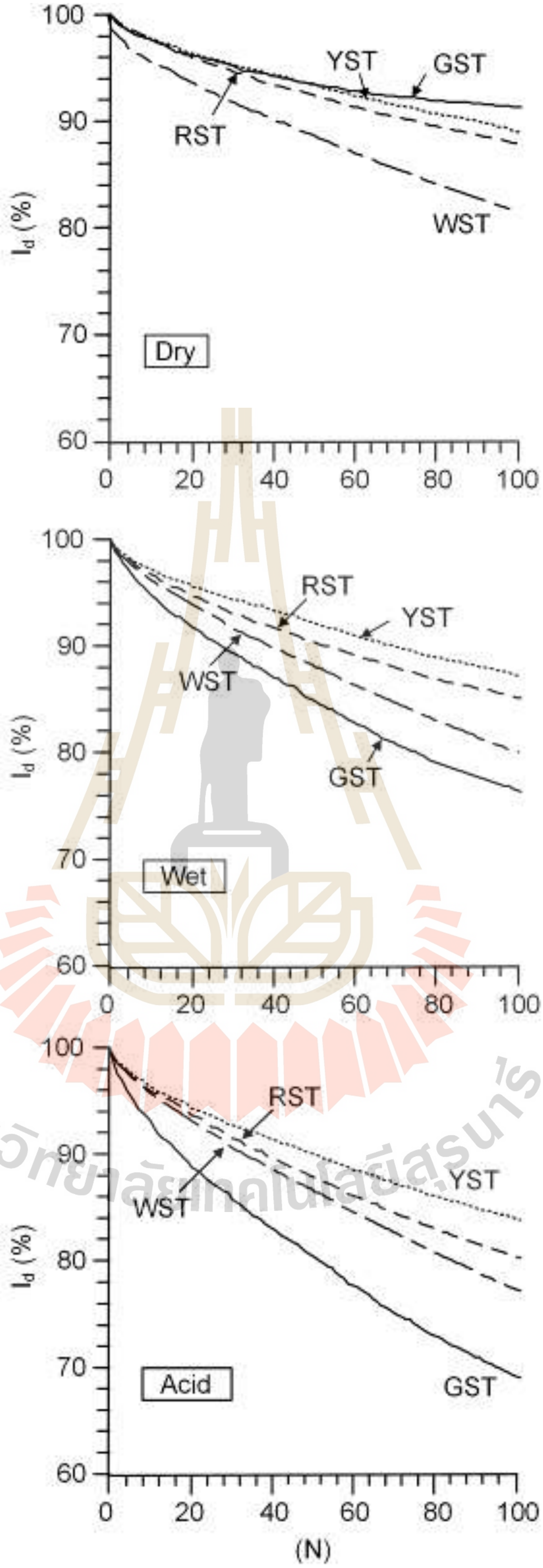


Figure 5.3 Slake durability index as a function of test cycle for sandstone group.

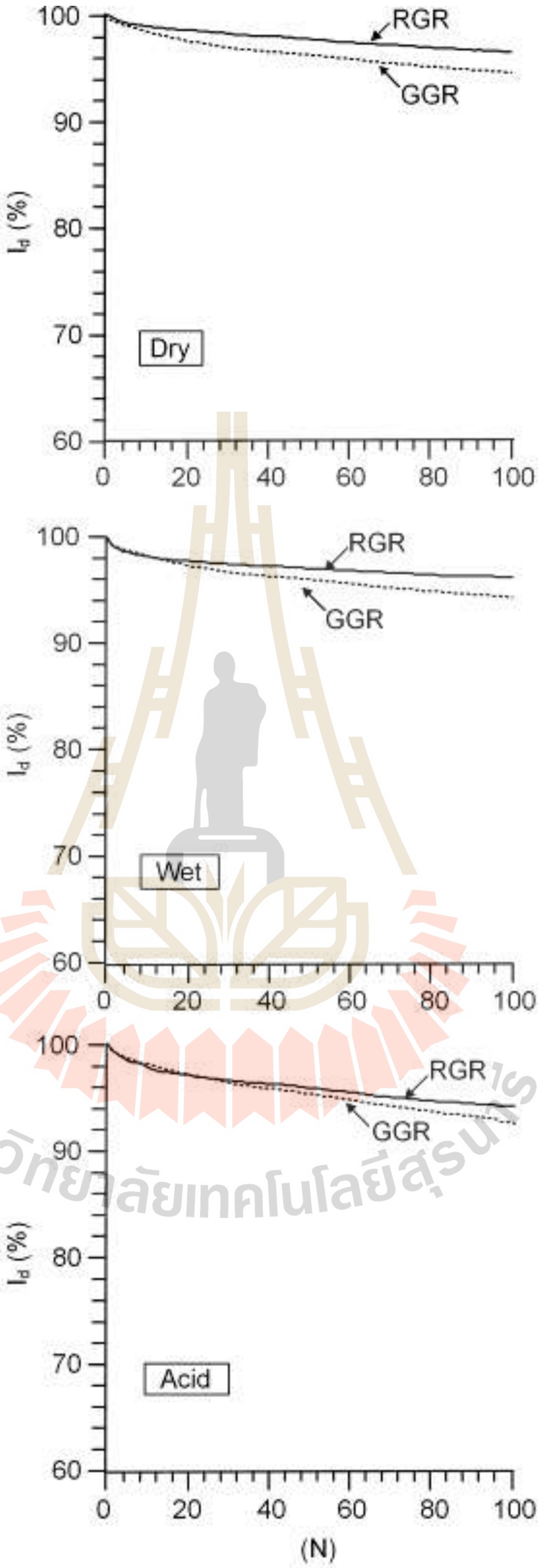


Figure 5.4 Slake durability index as a function of test cycle for granite group.

5.3 Water Absorption Test

Figures 5.5 through 5.8 show the water absorption as a function of test cycles (N). Water absorption measured from the rock fragments for every 20 cycles of testing. The ability to absorb water of fragments tends to reduce as the number of test cycles increases.

The water absorption of the rocks in basalt, carbonate, sandstone and granite group tends to show insignificant decrease under dry, wet and acidic conditions. The results of basalt group indicate that aphanitic basalt (BS), ferrous oxide basalt (FB) and vesicular basalt (VB) have water absorption value of 0.98%, 1.32% and 4.40%, up to 100 cycles. The vesicular basalt (VB) shows the highest water absorption value in the basalt group (Figure 5.5). For travertine (T) shows the highest water absorption value in the carbonate group. Limestone1 (SB1), limestone2 (SB2), Khao Khad marble (MB) and Khao Khad travertine (T) have average water absorption of 0.10%, 0.12%, 0.17 and 3.69%, (Figure5.6). The tested sandstones show various water absorption values. The calcareous lithic sandstone (GST), quartz sandstone (YST), white quartz sandstone (WST) and arkosic feldspathic sandstone (RST) have water absorption of 2.62%, 2.78%, 3.17 and 3.94%, respectively (Figure 5.7). Both granites show the lowest water absorption value. The pink granite (RGR) can absorb water slightly higher than the white granite (GGR) (Figure 5.8).

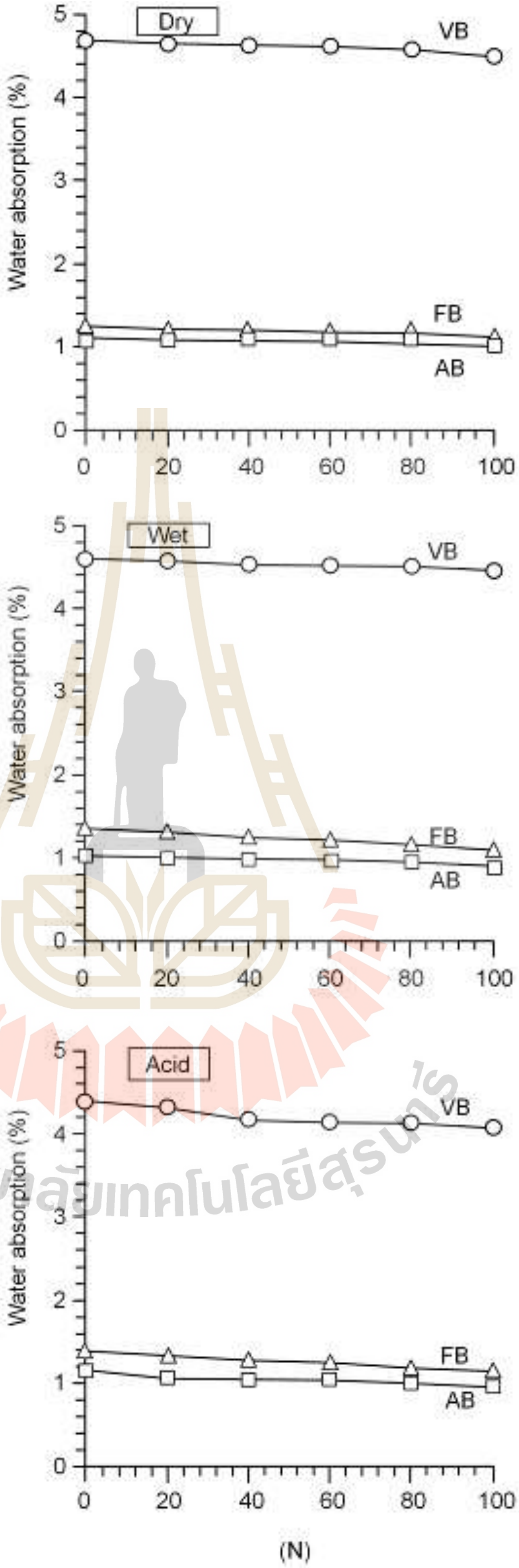


Figure 5.5 Water absorption as a function of test cycle for basalt group.

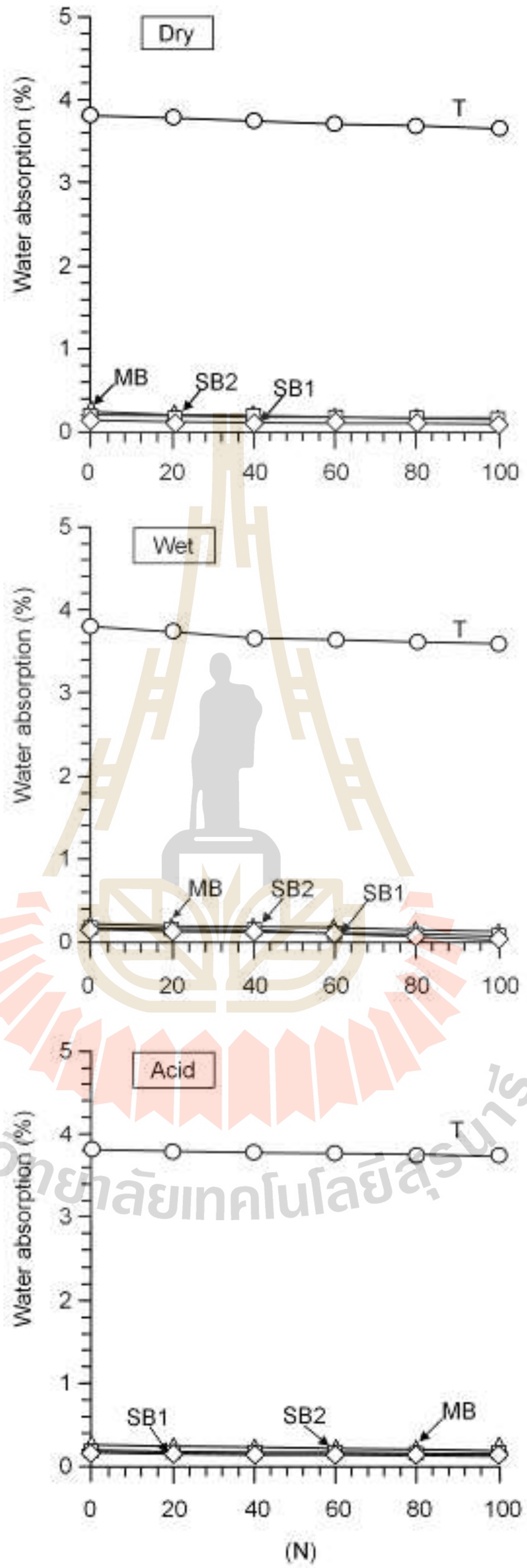


Figure 5.6 Water absorption as a function of test cycle for carbonate group.

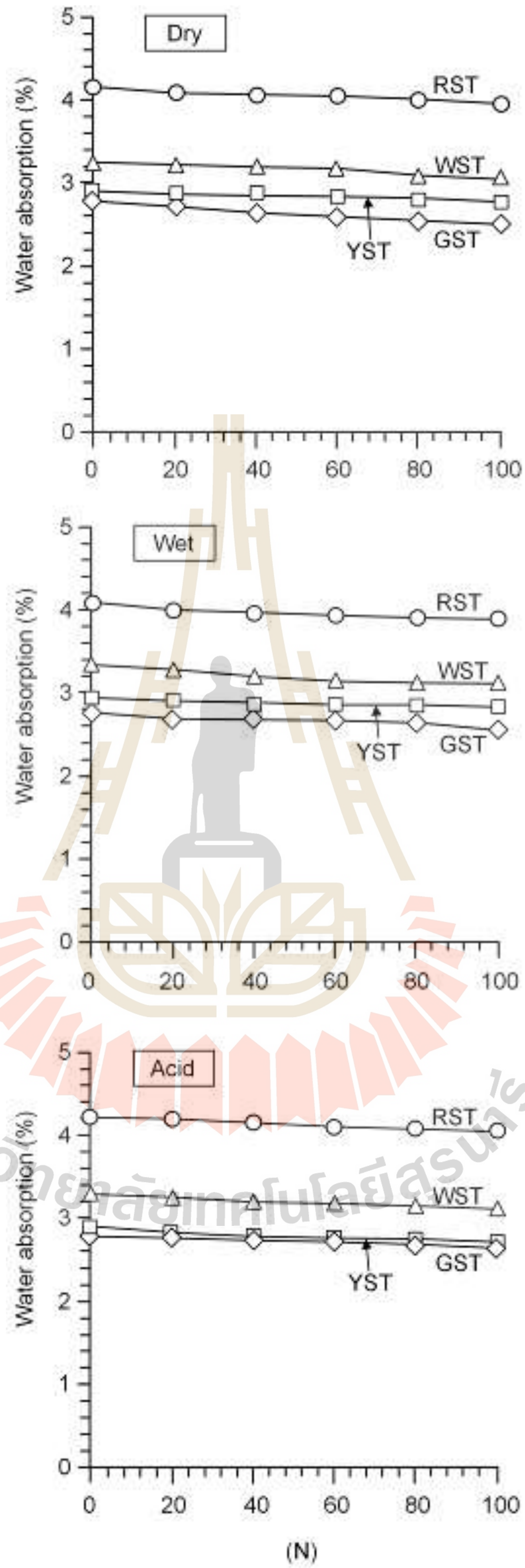


Figure 5.7 Water absorption as a function of test cycle for sandstone group.

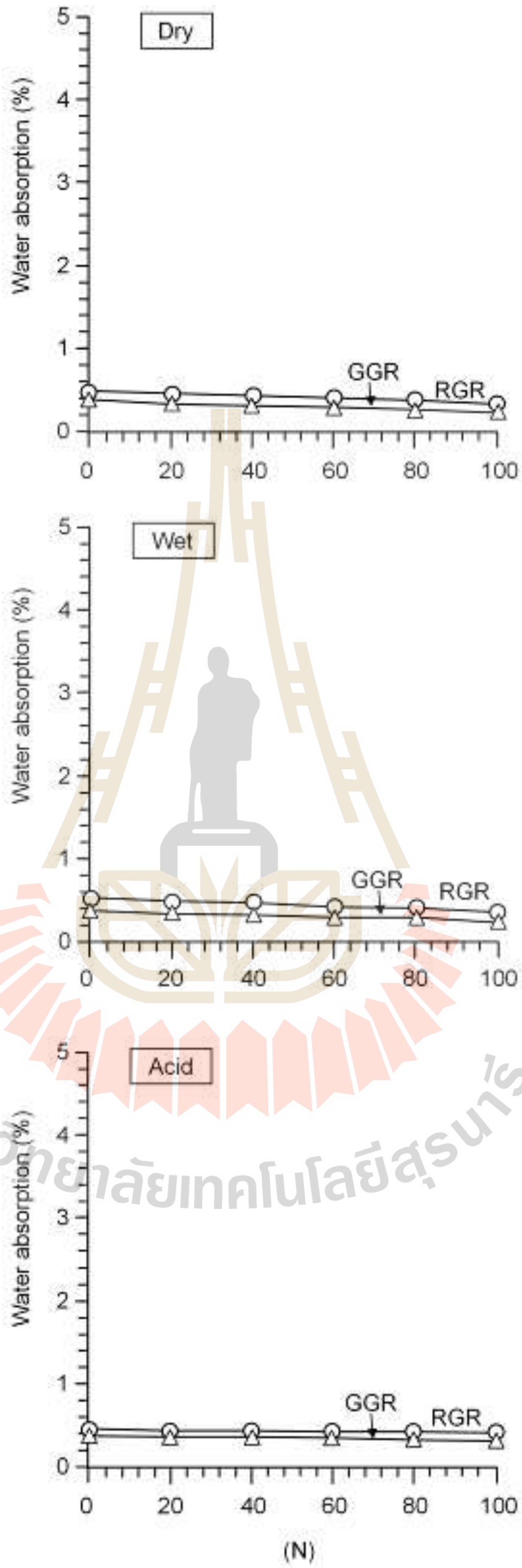


Figure 5.8 Water absorption as a function of test cycle for granite group.

5.4 Roughness and Sphericity of Specimens

The sphericity and roughness are determined from individual specimen in each group (Tables 5.1 to 5.4), based on widely used classification system given by Power (1982) (Figure 5.9). Estimated sphericity of sandstones and limestone under dry, wet and acid conditions tend to remain unchanged at about 4.5 (spherical). Both pink granite (RGR) and white granite (GGR) are 2.5 (sub discoidal) at initial. They increase to about 4.5 (spherical) under dry, wet and acidic conditions. The vesicular basalt (VB) is increase from 0.5 (discoidal) to 4.5 (spherical) under acidic condition (Figure 5.10).

Roughness of specimens tend to increase under initial, dry, wet and acidic conditions. As show in Figure 5.11. This suggests that the main mechanisms inducing the roundness of ten rock fragments are the scrubbing process and the chemical reaction of the fluid added in the drum. For granites tented here, the main mechanism inducing the roundness of the rock fragments seems to be only ten scrubbing process. Different types of fluid used in ten drum do not have significant impact on the roundness of granite fragments after 100 cycles of slaking.

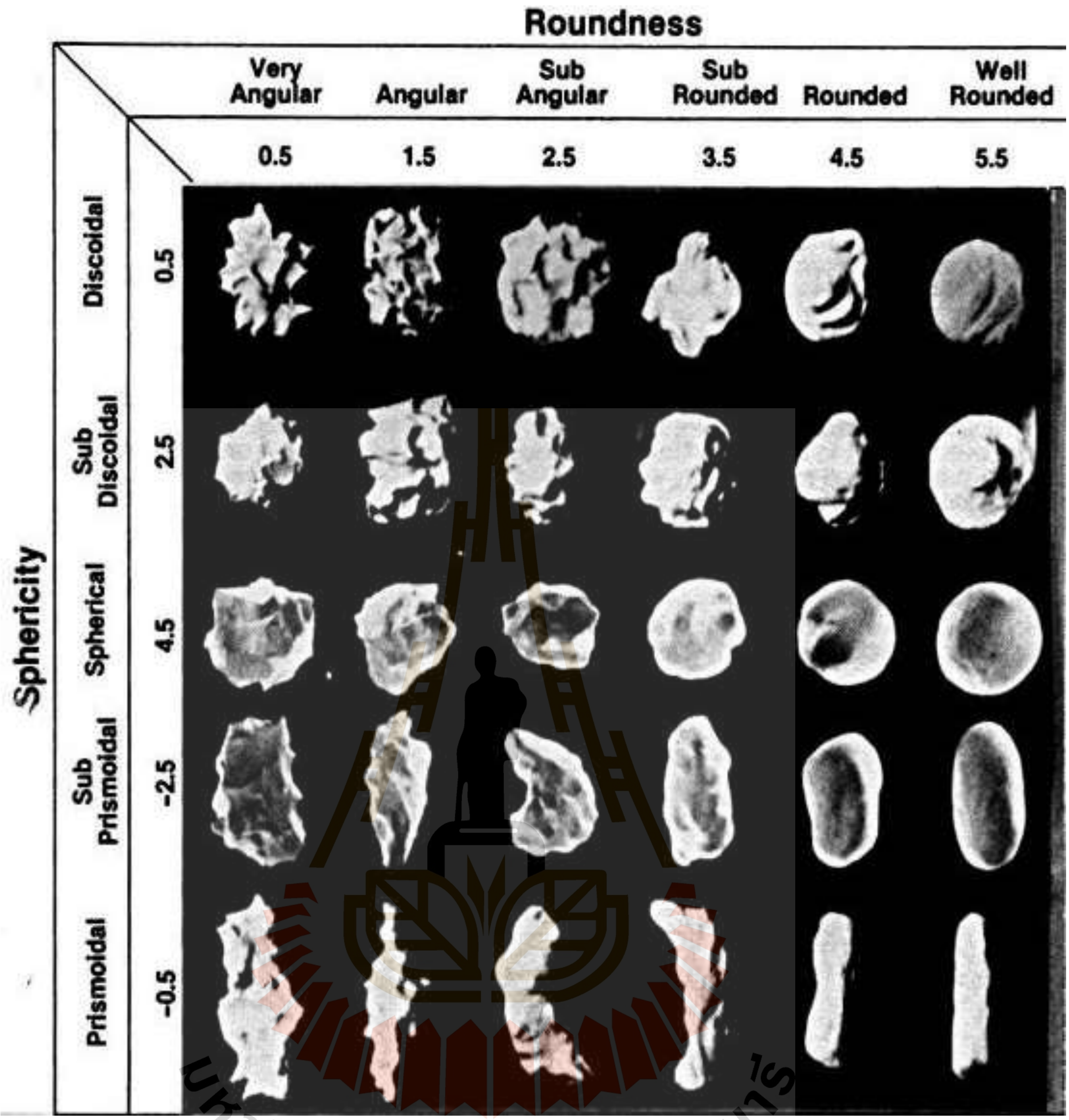


Figure 5.9 Modified visual comparison chart for estimating roundness and sphericity of granular materials (Powers, 1982).

Table 5.1 Pictures of basalt group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials.

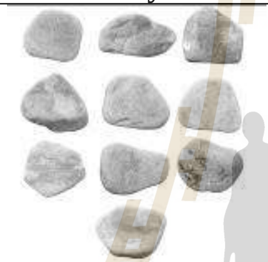
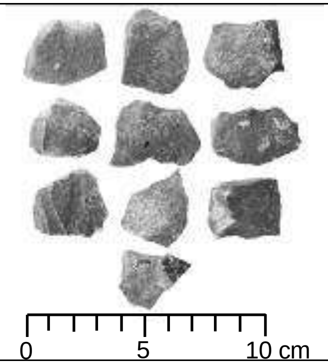
Rock Types	Initial	After 100 cycles		
		Dry	**Wet**	**Acid**
Aphanitic basalt (BS)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Sub rounded (3.5)	Rounded (4.5)
Ferrous oxide basalt (FB)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub angular (2.5)	Sub rounded (3.5)	Rounded (4.5)

Table 5.1 Pictures of basalt group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials (continue).

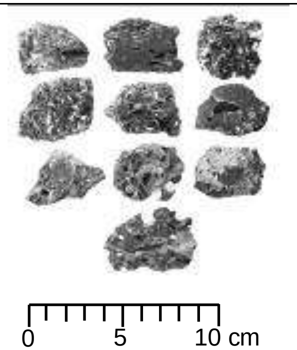
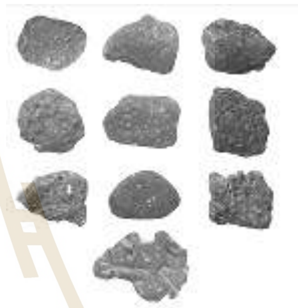
Rock Types	Initial	After 100 cycles		
		Dry	Wet	Acid
Vesicular basalt (VB)				
Sphericity	Discoidal (0.5)	Sub discoidal (2.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Sub angular (2.5)	Sub rounded (3.5)	Rounded (4.5)	Rounded (4.5)

Table 5.2 Pictures of carbonate group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials.

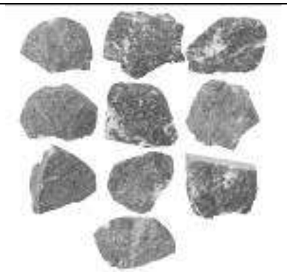
Rock Types	**Initial**	**After 100 cycles**		
		Dry	**Wet**	**Acid**
Limestone1 (L1)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub angular (2.5)	Sub rounded (3.5)	Rounded (4.5)
Limestone2 (L2)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub angular (2.5)	Sub rounded (3.5)	Rounded (4.5)

Table 5.2 Pictures of carbonate group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials (continue).

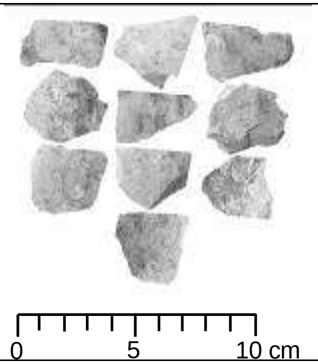
Rock Types	**Initial**	**After 100 cycles**		
		Dry	**Wet**	**Acid**
Khao Khad marble (MB))				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Rounded (4.5)	Rounded (4.5)
Khao Khad travertine (T)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub angular (2.5)	Rounded (4.5)	Rounded (4.5)

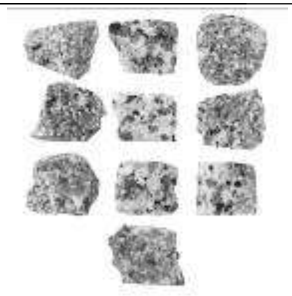
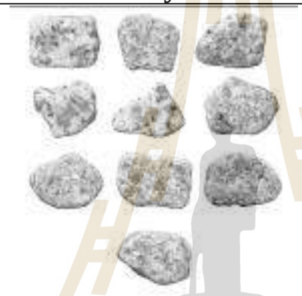
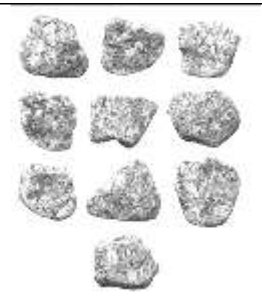
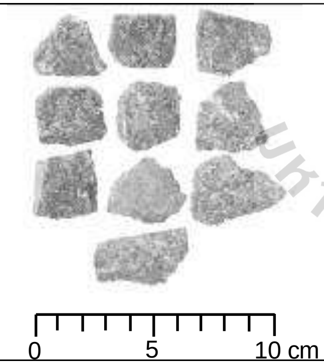
Table 5.3 Pictures of sandstone group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials.

Rock Types	Initial	After 100 cycles		
		Dry	Wet	Acid
Calcareous lithic sandstone (GST)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Rounded (4.5)	Well rounded (5.5)
Quartz sandstone (YST)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub angular (2.5)	Sub rounded (3.5)	Sub rounded (3.5)

Table 5.3 Pictures of sandstone group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials (continue).

Rock Types	Initial	After 100 cycles		
		Dry	Wet	Acid
Arkosic feldspathic sandstone (RST)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Rounded (4.5)	Rounded (4.5)
White quartz sandstone (WST)				
Sphericity	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Rounded (4.5)	Well rounded (5.5)

Table 5.4 Pictures of granite group before and after 100 cycles of slake durability test and estimating rounded and sphericity of granular materials.

Rock Types	Initial	After 100 cycles		
		Dry	Wet	Acid
White granite (GGR)				
Sphericity	Sub discoidal (2.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Sub rounded (3.5)	Sub rounded (3.5)
Pink granite (RGR)				
Sphericity	Sub discoidal (2.5)	Spherical (4.5)	Spherical (4.5)	Spherical (4.5)
Roundness	Angular (1.5)	Sub rounded (3.5)	Sub rounded (3.5)	Sub rounded (3.5)

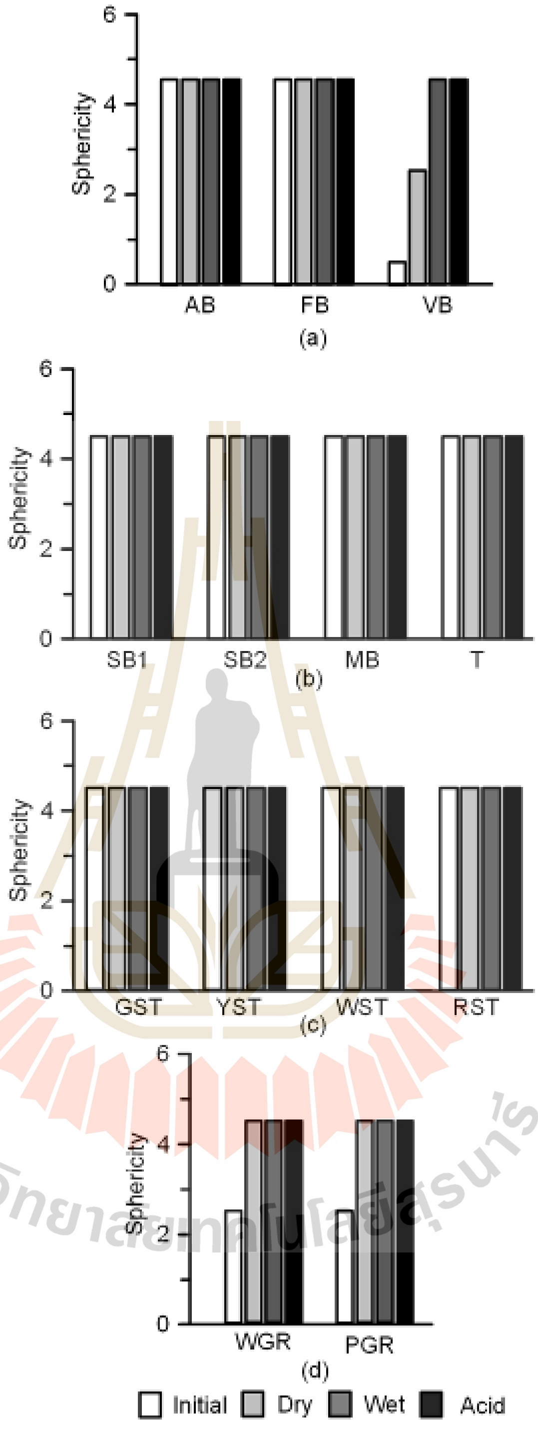


Figure 5.10 Chart for visual estimate of sphericity of basalt (a), carbonate (b), sandstone (c) and granite (d) group as suggested by Power (1982).

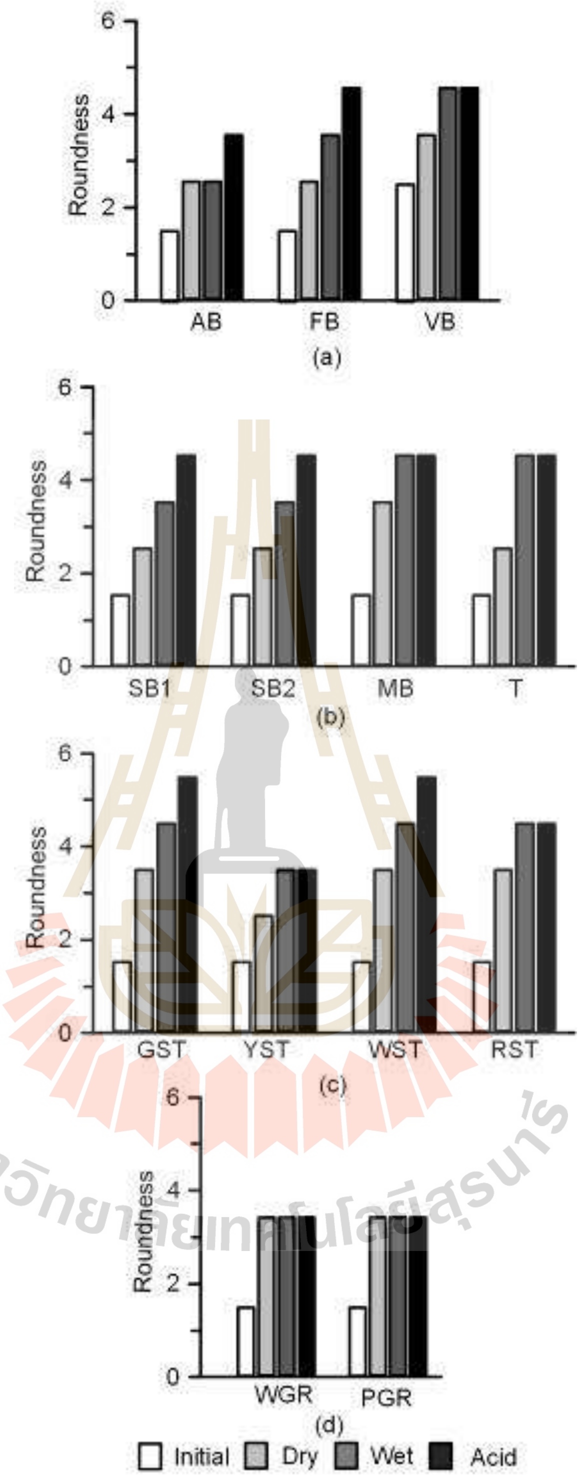


Figure 5.11 Chart for visual estimate of roundness of basalt (a), carbonate (b), sandstone (c) and granite (d) group as suggested by Power (1982).

5.5 X-ray Diffraction Test

Specimens from initial condition and those obtained after 100 cycles of slake durability test were prepared by crushing each lump until all passing mesh number 60. These powders were separated by using chute splitter (Figure 5.12) to obtain 10 grams based on the ASTM (B215-15). The X-ray diffractormeter-D2 phaser (XRD) (Figure 5.13) is used in the analysis to obtain their mineral compositions.

The X-ray diffraction test (XRD) was performed in order to obtain a qualitative evaluation for the collected mineral values. Individual mineral values cannot be evaluated from natural rock samples, but the overall performance of the technique can be judged by the departure of sum from 100%. These results are evaluated by slake durability index result, modified results are more reduce than initial under conditions (dry, wet and acid) (Tables 5.5 to 5.8).

For basaltic group, the main changes of the mineral compositions seem to be the reductions of calcite, plagioclase and pyroxene (Figure 5.14 a, b and c). This may cause by the scrubbing process during slaking cycle. The effect of fluids is unclear, because there is not trend of the change of mineral composition unless different test conditions.

Virtually all minerals composed in the limestone group reduce from initial, dry wet and acidic conditions. These mineral content reductions are likely to cause by both scrubbing and chemical reaction process.

Similar to the limestone group, the sandstone group also shows the reduction of mineral contents, especially calcite (Figure 5.15a and b). Again this may cause by both mechanical and chemical processes occurring the slaking cycles.

For granite group, the reduction of the mineral contents seems to be only these except quartz (Figure 5.15c). Nevertheless, their reductions proportion seems to be lower than the other three rock group.

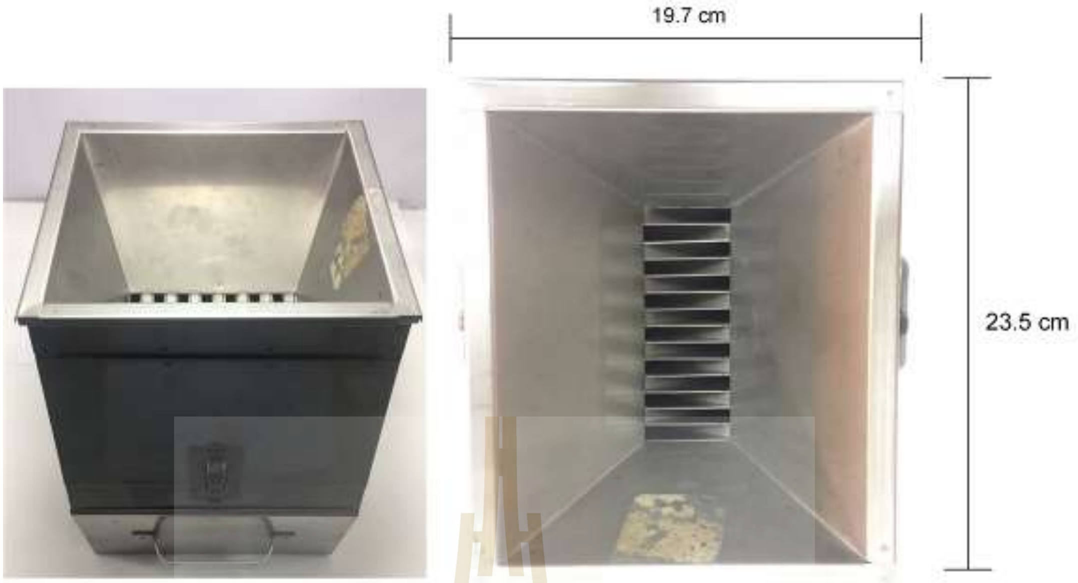


Figure 5.12 Chute splitter for sample separation.

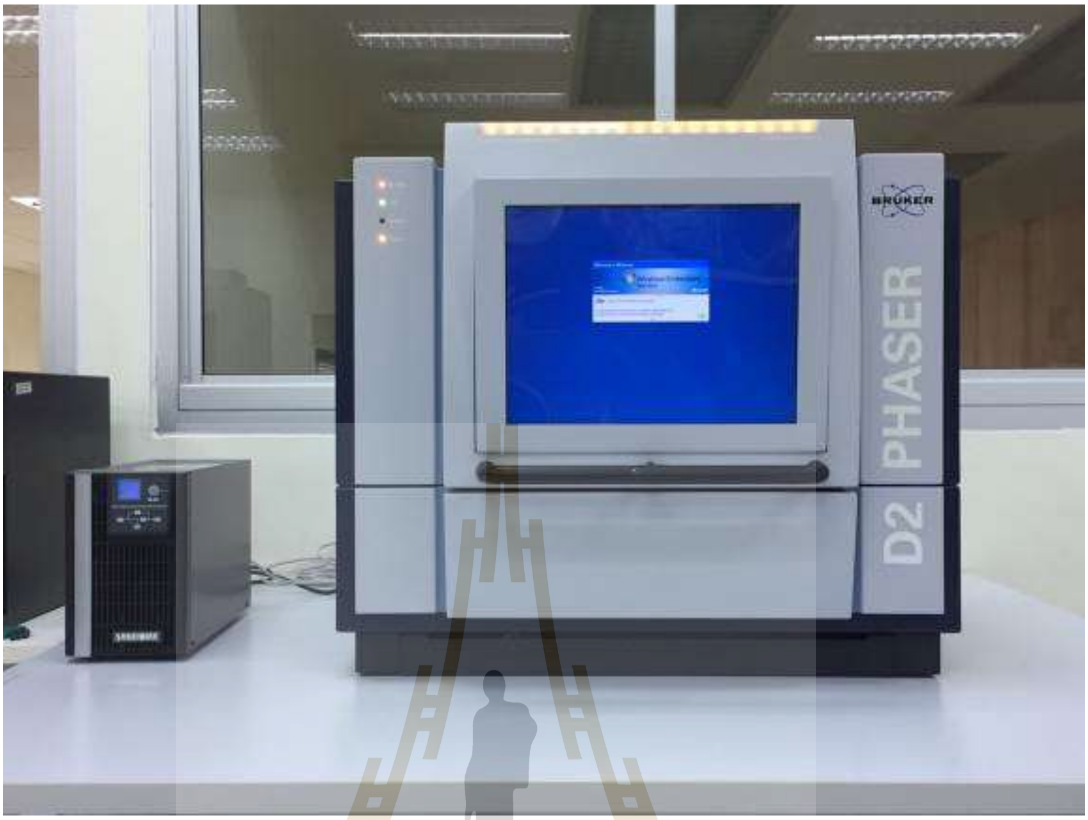


Figure 5.13 X-ray diffractrometer-D2 phaser.

Table 5.5 Results of XRD analysis for basalt group before (initial) and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Aphanitic Basalt (AB)	Calcite	8.57	7.85	7.05	6.82
	Microcline	11.14	8.13	7.72	11.03
	Olivine	8.50	8.44	8.38	5.55
	Plagioclase	50.70	50.52	50.69	47.44
	Pyroxene	21.09	19.84	19.87	18.78
	Total	100.01	94.78	93.70	89.62
Ferrous Oxide Basalt (FB)	Calcite	6.77	5.94	5.35	3.51
	Magnetite	4.24	3.58	3.49	2.55
	Microcline	15.12	15.03	13.75	14.19
	Olivine	1.34	1.11	1.05	1.00
	Plagioclase	56.76	52.14	52.94	48.56
	Pyroxene	15.78	14.51	13.94	15.43
	Total	100.01	92.31	90.52	85.24
Vesicular Basalt (VB)	Calcite	13.48	8.82	8.71	7.74
	Microcline	14.16	11.98	13.13	13.21
	Olivine	7.40	4.37	4.24	3.94
	Plagioclase	46.33	46.25	43.81	43.27
	Pyroxene	18.63	13.52	14.10	13.35
	Total	100.00	84.94	83.99	81.51

Table 5.6 Results of XRD analysis for carbonate group before (initial) and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Limestone 1 (SB1)	Calcite	81.66	78.08	77.19	74.08
	Dolomite	1.03	0.53	0.46	0.48
	Mica	0.82	0.67	0.65	0.43
	Quartz	16.49	15.23	15.47	15.55
	Total	100.00	94.51	93.77	90.54
Limestone 2 (SB2)	Calcite	95.80	90.09	89.47	86.52
	Dolomite	2.46	2.05	1.63	1.38
	Mica	0.44	0.21	0.24	0.24
	Quartz	1.30	0.78	0.92	0.68
	Total	100.00	93.13	92.26	88.82
Khao Khad Marble (MB)	Calcite	98.85	86.62	85.16	79.82
	Mica	1.15	0.44	0.34	0.18
	Total	100.00	87.06	85.50	80.00
Khao Khad Travertine (T)	Calcite	96.51	90.17	85.97	75.80
	Dolomite	1.70	0.81	0.71	0.51
	Mica	1.21	0.26	0.20	0.17
	Quartz	0.58	0.32	0.29	0.12
	Total	100.00	91.56	87.17	76.60

Table 5.7 Results of XRD analysis for sandstone group before(initial) and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Calcareous Lithic Sandstone (GST)	Albite	29.01	27.73	22.42	21.88
	Calcite	4.75	4.64	2.28	1.69
	Chloride	14.45	13.12	11.92	9.29
	Muscovite	7.89	6.96	5.76	3.45
	Quartz	43.90	38.90	33.91	32.67
	Total	100.00	91.36	76.29	68.96
Quartz Sandstone (YST)	Feldspar	2.45	1.49	1.32	2.05
	Kaolinite	7.73	6.86	6.56	6.48
	Mica	0.47	0.38	0.15	0.14
	Quartz	89.35	80.28	79.11	75.14
	Total	100.00	89.01	87.15	83.81
White Quartz Sandstone (WST)	Feldspar	1.62	1.60	0.94	0.42
	Kaolinite	9.09	6.12	6.08	5.34
	Mica	0.33	0.31	0.14	0.00
	Quartz	88.96	73.39	72.14	71.41
	Total	100.00	81.42	79.30	77.17
Arkosic Feldspathic Sandstone (RST)	Albite	42.97	40.65	38.42	36.41
	Calcite	6.38	0.23	0.21	0.13
	Feldspar	5.51	2.72	4.58	3.02
	Mica	0.66	0.46	0.44	0.51
	Quartz	44.49	43.83	41.39	40.11
	Total	100.01	87.89	85.04	80.18

Table 5.8 Results of XRD analysis for granite group before (initial) and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Pink Granite (RGR)	Amphibole	1.25	0.57	0.88	0.56
	Orthoclase	42.58	41.89	41.72	40.21
	Plagioclase	22.32	21.90	21.29	20.70
	Quartz	33.86	32.11	32.38	32.61
	Total	100.01	96.47	96.27	94.08
White Granite (GGR)	Biotite	3.96	1.04	1.16	1.60
	Orthoclase	19.83	19.21	18.44	18.49
	Plagioclase	26.08	24.60	25.17	24.29
	Quartz	50.13	49.77	49.76	48.08
	Total	100.00	94.62	94.53	92.46

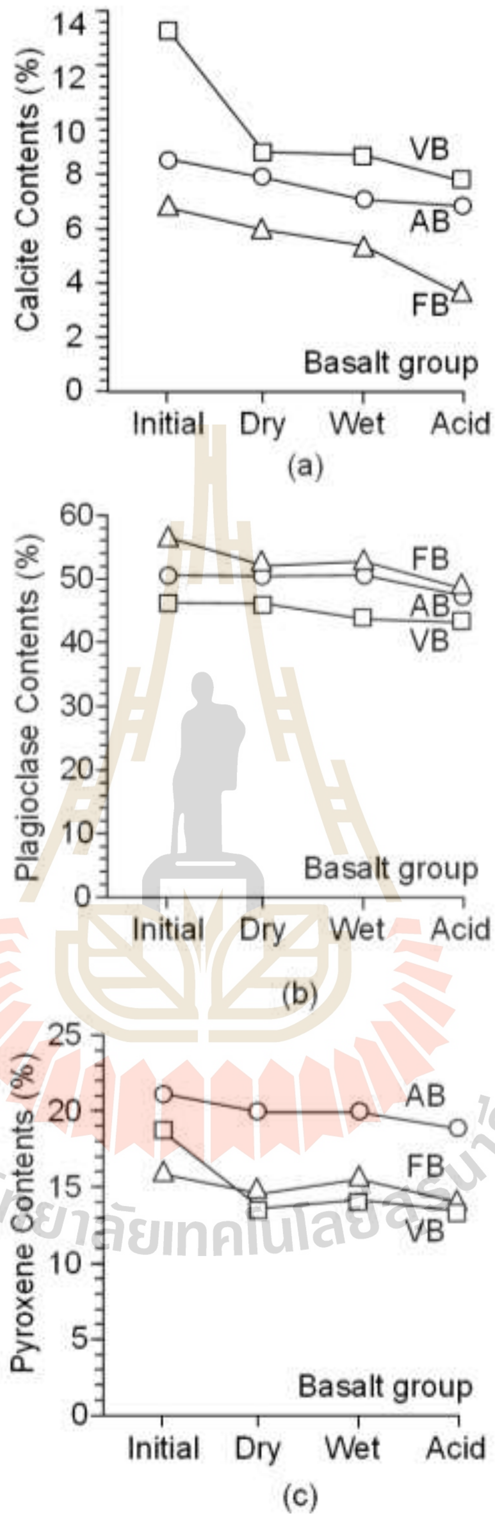


Figure 5.14 Mineral content of basalt group.

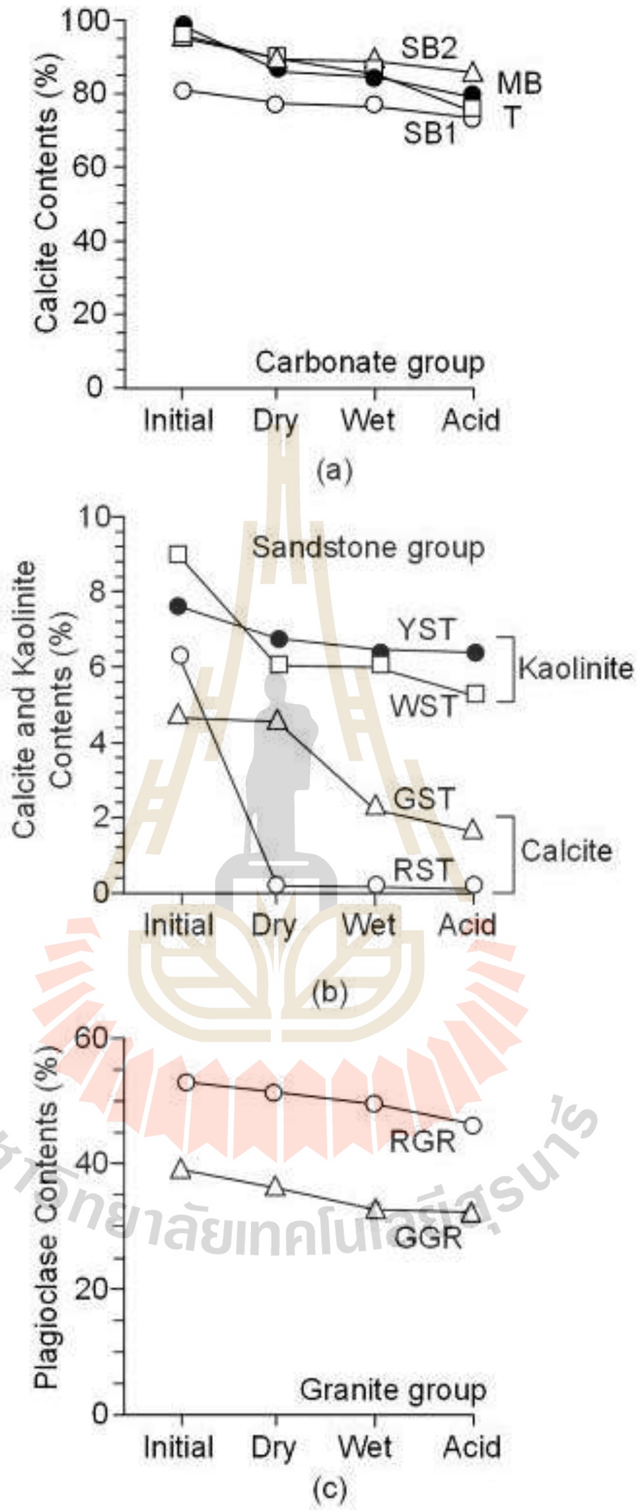


Figure 5.15 Mineral content of carbonate, sandstone and granite groups.

CHAPTER VI

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Discussions

Factors affecting the degradation of the sedimentary rocks used in this study seem to be the packing density, grain contact characteristics and kaolinite content. Rocks with higher density and lower percentage of cementing materials (grain to grain contact) tend to degrade slower than those with lower density and higher amount of cementing materials. Kaolinite is highly sensitive to water which makes the rock disintegrated quickly. These observations agree reasonable well with those observed by Koncagul and Santi (1999).

For the volcanic rocks, calcite content seems to be significant factor affecting the rate of degradation, particularly when they are under wet and acidic conditions. The pore spaces in volcanic rock also enhance the weathering process by allowing more fluid to penetrate into the inner matrix.

For carbonate rocks, rich calcium carbonate and/or magnesium carbonate content seems to be significant factor affecting the rate of weathering, particularly when subjected to acid solution. This agrees with the results performed by Ghobadi and Momeni (2011). The sulfuric acid with pH=5.6 concentration used here represents acid rain in southeast Asia based on the measurements of EANET by Lee (2016).

Rocks rich in quartz, feldspar and muscovite are independent of pH of slaking fluid. These observations agree reasonable well with those observed by Gupta and Ahmed (2007). The olivine weathers rapidly because the silicon tetrahedral is only held together by oxygen and the metal cations which form weak bonds. In contrast, quartz is very resistant, because it consists entirely of linked silicon tetrahedral. Accordingly, the olivine and magnetite mineral, ferrous component, are durability factors of ferrous rock decrease with increase in the acidic solutions. This agrees with the results performed by Singh et al. (2001). Weathering depends on many factors including fluid penetrate on surface specimens. The efficient penetration of different rocks into a kaolinitic saprolite.

The degradation of slake durability index test under wet condition is greater than dry condition, which involves ability to absorb water of the rock fragment. The slake durability index test cycles increase the scrubbing process and slowly remove the outer matrix of comparatively fresh which have lesser amounts of pore spaces as compared to the outer part. This agrees with those obtained by Fuenkajorn and Sri-in (2009) and Walsri et al. (2012).

Rocks consisting of coarse fragments such as granite easily weather physically but do not weather chemically. In contrast, rocks consisting of fine fragments, such as basalt, chemically weather quicker than physical weathering.

6.2 Conclusions

The slake durability index test up to 100 cycles under dry, wet and acidic conditions are performed. Thirteen rock types that are commonly encountered in the north and northeast of Thailand have been used as rock samples. X-ray powder diffraction analyses are also performed to determine changes of mineral compositions of the rock specimens.

The results obtained from the I_d tests indicate that factors controlling the degradation rate of the sedimentary rocks are primarily density, grain contact, and kaolinite content. For the volcanic rocks, grain size, porosity, mica and kaolinite contents are the primary factors controlling the rock degradation. Though not sensitive to water, rocks containing mica may disintegrate easily under cyclic changes of temperatures. The impacts of calcite and water absorption on the rock degradation are more prominent when the rocks subjected to water and acid than subjected under dry condition.

The water absorption measurements show the increasing of the effective porosity of the rocks with increasing number of slaking cycles. The slake durability index testing up to 100 cycles of the rock types is insignificant for water absorption value although acidic condition is chemical weathering, catalyst changed minerals property.

The x-ray powder diffraction (XRD) for each rock type is performed to determine quantity of mineral loss from slaking test under different conditions. The results indicate that amount of weight loss depends on the decreasing quantity of minerals under each condition. The loss of calcite or kaolinite is prominent factors for basalt, carbonate and sandstone groups. The reduction of mineral contents seem to be insignificant for granite group.

6.3 Recommendations for future studies

The uncertainties and adequacies of the research investigation and results discussed above lead to the recommendations for further studies, as follows.

1. Diverse rock types, compositions and textures are required in order to truly assess all factors affecting the rock degradation. The sedimentary and weak volcanic rocks should have a wide range of grain (crystal) sizes, rock forming minerals, packing density (apparent porosity) and textures.
2. Sample density should be determined throughout the slaking cycle to assess the changes of rock porosity.
3. Mechanical property testing, such as point load index, may be desirable to determine the changes of rock strengths as subjected to different numbers of slaking cycles.
4. Slake durability index test should be conducted under carbonic acid to simulate natural acid rain condition.

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APPENDIX A

RESULTS OF X-RAY DIFFRACTION MEDTHOD

Table A.1 Results of XRD analysis for basalt group before and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Aphanitic Basalt (AB)	Calcite	8.57	8.28	7.52	7.61
	Microcline	11.14	8.58	8.24	12.31
	Olivine	8.50	8.91	8.94	6.19
	Plagioclase	50.70	53.30	54.09	52.94
	Pyroxene	21.09	20.93	21.20	20.96
	Total	100.00	100.00	100.00	100.00
Ferrous Oxide Basalt (FB)	Calcite	6.77	6.43	5.91	4.12
	Magnetite	4.24	3.88	3.86	2.99
	Microcline	15.12	16.28	15.19	16.65
	Olivine	1.34	1.20	1.16	1.17
	Plagioclase	56.76	56.48	58.49	56.98
	Pyroxene	15.78	15.72	15.40	18.10
	Total	100.01	100.00	100.01	100.01
Vesicular Basalt (VB)	Calcite	13.48	10.38	10.37	9.49
	Microcline	14.16	14.10	15.63	16.21
	Olivine	7.40	5.14	5.05	4.83
	Plagioclase	46.33	54.45	52.16	53.08
	Pyroxene	18.63	15.92	16.79	16.38
	Total	100.00	100.00	100.00	99.99

Table A.2 Results of XRD analysis for carbonate group before and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Limestone 1 (SB1)	Calcite	81.66	82.61	82.33	81.82
	Dolomite	1.03	0.56	0.49	0.53
	Mica	0.82	0.71	0.69	0.47
	Quartz	16.49	16.11	16.50	17.17
	Total	100.00	99.99	100.01	100.00
Limestone 2 (SB2)	Calcite	95.80	96.74	96.97	97.41
	Dolomite	2.46	2.20	1.77	1.55
	Mica	0.44	0.23	0.26	0.27
	Quartz	1.30	0.84	1.00	0.77
	Total	100.00	100.01	99.99	100.00
Khao Khad Marble (MB)	Calcite	98.85	99.50	99.60	99.78
	Mica	1.15	0.51	0.40	0.23
	Total	100.00	100.01	100.00	100.01
Khao Khad Travertine (T)	Calcite	96.51	98.48	98.62	98.97
	Dolomite	1.70	0.88	0.81	0.67
	Mica	1.21	0.28	0.23	0.22
	Quartz	0.58	0.35	0.33	0.16
	Total	100.00	100.00	100.00	100.01

Table A.3 Results of XRD analysis for sandstone group before and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Calcareous Lithic Sandstone (GST)	Albite	29.01	30.36	29.39	31.73
	Calcite	4.75	5.08	2.99	2.45
	Chloride	14.45	14.36	15.62	13.47
	Muscovite	7.89	7.62	7.55	5.00
	Quartz	43.90	42.59	44.45	47.38
	Total	100.00	100.00	99.99	100.03
Quartz Sandstone (YST)	Feldspar	2.45	1.67	1.51	2.45
	Kaolinite	7.73	7.71	7.53	7.73
	Mica	0.47	0.43	0.17	0.17
	Quartz	89.35	90.20	90.78	89.65
	Total	100.00	100.01	100.00	100.00
White Quartz Sandstone (WST)	Feldspar	1.62	1.96	1.19	0.54
	Kaolinite	9.09	7.52	7.67	6.92
	Mica	0.33	0.38	0.18	0.00
	Quartz	88.96	90.13	90.97	92.54
	Total	100.00	99.99	100.00	100.00
Arkosic Feldspathic Sandstone (RST)	Albite	42.97	46.25	45.18	45.41
	Calcite	6.38	0.26	0.25	0.16
	Feldspar	5.51	3.09	5.39	3.77
	Mica	0.66	0.52	0.52	0.64
	Quartz	44.49	49.87	48.67	50.03
	Total	100.01	100.01	100.00	100.00

Table A.4 Results of XRD analysis for granite group before and after 100 cycles of slake durability test.

Rock Type	Mineral	Initial (%)	Conditions		
			Dry (%)	Wet (%)	Acid (%)
Pink Granite (RGR)	Amphibole	1.25	0.59	0.91	0.60
	Orthoclase	42.58	43.42	43.34	42.74
	Plagioclase	22.32	22.70	22.12	22.00
	Quartz	33.86	33.28	33.64	34.66
	Total	100.01	100.00	100.00	99.99
White Granite (GGR)	Biotite	3.96	1.10	1.23	1.73
	Orthoclase	19.83	20.32	19.49	20.00
	Plagioclase	26.08	26.03	26.60	26.27
	Quartz	50.13	52.66	52.59	52.00
	Total	100.00	100.01	100.01	100.00

BIOGRAPHY

Mister Phongsakorn Torsangtham was born on October 20, 1994 in Nakhon Ratchasima Province, Thailand. He received his Bachelor’s Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2017. For his post-graduate, he continued to study with a Master’s degree in Civil, Transportation and Geo-resources Engineering Program, Institute of Engineering, Suranaree University of Technology. During graduation, 2017-2019, he was a part time worker in position of research assistant at the Geomechanics Research Unit, Institute of Engineering, Suranaree University of Technology.