LARGE-SCALED SLAKE DURABILITY INDEX TESTS OF SOME WEAK ROCKS

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การทดสอบดัชนีความคงทนต่อการผุกร่อนในสเกลใหญ่ของหินเนื้ออ่อนบางชนิด

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LARGE-SCALED SLAKE DURABILITY INDEX TESTS OF SOME WEAK ROCKS

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

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วัตถุประสงค์ของงานวิจัยนี้ คือ เพื่อศึกษาหาผลกระทบของการผุกร่อนของหินเนื้ออ่อนบางชนิดด้วยวิธีทดสอบดัชนีความคงทนต่อการผุกร่อนในสเกลใหญ่ และคาดคะเนความแข็งของหินในเชิงเวลา กิจกรรมหลักประกอบด้วยการจำลองการผุกร่อนของตัวอย่างหิน การศึกษาคุณสมบัติเชิงกายภาพและเชิงกลศาสตร์ของหินภายใต้สภาวะการผุกร่อนที่ต่างกัน และการทดสอบดัชนีความคงทนต่อการผุกร่อนแบบเปียกและแห้ง การทดสอบได้ดำเนินการในตัวอย่างหินทราย 3 ชนิด ที่พบมากในภาคตะวันออกและตะวันออกเฉียงเหนือของประเทศไทย โดยเตรียมตัวอย่างหินอย่างน้อย 10 ตัวอย่างของหินแต่ละชนิดและแต่ละการทดสอบ ผลจากการทดสอบที่ได้บ่งชี้ว่าการทดสอบของหินที่มีขนาดใหญ่มีแนวโน้มการคาดคะเนการผุกร่อนของหินได้ดีกว่าหินที่มีขนาดเล็กสาเหตุเนื่องมาจากมีพลังงานในการกระทบกันของหินที่มากขึ้น จากผลการทดสอบของหินทรายทั้งหมดแสดงให้เห็นว่ามีการสูญเสียน้ำหนักมากกว่าเมื่อถูกทดสอบในหินขนาดใหญ่ โดยเปรียบเทียบกับการทดสอบในหินขนาดเล็ก ซึ่งช่วยให้ความสัมพันธ์มีความถูกต้องแม่นยำขึ้นตามสภาวะจริงที่เกิดขึ้นในภาคสนาม หินทรายทุกชนิดมีความอ่อนไหวต่อน้ำ หินทรายชุดโคกกรวดแสดงความอ่อนไหวต่อน้ำมากกว่าหินทรายอีกสองชนิด การทดสอบค่ากำลังการกดในแกนเดียวจะลดลงต่างจากการทดสอบดัชนีการผุกร่อนที่ได้รับจากค่า ΔSDI ที่เพิ่มขึ้น ผลจากการทดสอบการจำลองการผุกร่อนใกล้เคียงกับการจำลองในสภาวะจริงโดยเปรียบเทียบค่าพลังงานความร้อนที่หินได้ดูดซับในระหว่างการจำลองแบบเดียวกับการทดสอบในสภาวะจริง จากผลการคำนวณพบว่าหนึ่งวัฏจักรร้อน-เย็นที่ทำการทดสอบในห้องปฏิบัติการเทียบเท่ากับ 18 วันภายใต้สภาวะจริง ความสัมพันธ์นี้สามารถให้การคาดคะเนความแข็งของหินและความคงทนของหินของหินทรายหลังจากสัมผัสกับบรรยากาศ

สาขาวิชาเทคโนโลยีธรณี ลายมือชื่อนักศึกษา ____________________

ปีการศึกษา 2553 ลายมือชื่ออาจารย์ที่ปรึกษา_______________

SUKANDA RINTRAWILAI : LARGE-SCALED SLAKE DURABILITY INDEX TESTS OF SOME WEAK ROCKS. THESIS ADVISOR : ASSOC. PROF. KITTITEP FUENKAJORN, Ph.D., P.E., 75 PP.

WEATHERING/SIMULATION/DEGRADATION/SLAKING

The objectives of this research are to experimentally determine the effects of weathering processes on some weak rocks using large-scaled slake durability testing and to predict the rock strength as a function of time. The effort primarily involves simulation of the weathering-induced degradation of rock specimens, determination of the physical and mechanical properties of the rocks at various stages of degradation, and conducting wet and dry slake durability testing. The tests are carried out on three sandstone members that are commonly encountered in the east and northeast of Thailand. A minimum of ten rock samples are prepared for each rock type and each test condition. The results indicate that the large-scaled test results tend to predict the rock deterioration better than the small-scaled results do, primarily due to the greater energy imposed to the rock fragments. All tested sandstones show a greater weight loss when they are tested with large rock fragments compared to the small rock fragments. This allows a better correlation with the actual in-situ conditions. All tested sandstones are sensitive to water. Khok Kruat sandstone shows the greatest water-sensitivity than do the other two. The uniaxial compressive strength test decreases as the difference in slake durability indices obtained from adjacent cycles (ΔSDI) increases. The results of the rock degradation simulation are related to the actual in-situ conditions by comparing the heat energy absorbed by rock specimens during the simulation with those measured in the actual in- situ condition.

The calculation suggests that one heating-cooling cycle made in the laboratory is equivalent to 18 days under in-situ condition. This correlation allows predicting the rock strength and durability of the sandstones after exposing to the atmosphere.

School of Geotechnology Student's Signature ________________

Academic Year 2010 Advisor's Signature________________

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Sukanda Rintrawilai

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LIST OF SYMBOLS AND ABBREVIATIONS

a = Multiplie Factor

Cp = Specific Heat Capacity

c = Cohesion

c_0 = Basic Strength of Rock Specimen

D = Day

E = Elastic modulus

F.S = Factor Safety of Slope

I_d = Slake durability Index Test Values

m = Weight of Rock Specimen

N = Cycle of Number Slake Durability Index Test

N* = Backward Cycle of Number Slake Durability Index Test

n = Cycle of Heating and Cooling Simulation

Q = Absorbed Energy of Rock Specimen

SDI = Slake Durability Index Test

t = Time of Interval of Energy absorption

ΔT = Difference of Temperature

ΔSDI = Different Slake Durability Index Test

y = Strength of Rock Specimen

m = Slope of Rock Specimen

x = Time

LIST OF SYMBOLS AND ABBREVIATIONS (Continued)

α = Coefficient of Rate Weathering

β = Coefficient of Time Weathering

δ = Empirical Constant

η = Exponent of Strength Decrease

ν = Poisson’s ratio

σ_c = Uniaxial Compressive Strength

$\sigma_{c,o}$ = Uniaxial Compressive Strength of Actual Environment Rock

$\sigma_{c,s}$ = Uniaxial Compressive Strength of Laboratory Simulation Rock

σ_n = Normal Stress

CHAPTER I

INTRODUCTION

1.1 Background of problems and significance of the study

In geotechnical investigations involved with surface and subsurface structures, the evaluation of strength and deformability of rock and rock mass is frequently needed. These measurements become more difficult if the rocks encountered are influenced by weathering. The study of strength and deformational behavior of rock under uniaxial compression condition is of vital importance, and not only provides basic material characteristics or design indices but also serves as useful data in analysis where the rocks are at a shallow depth. Most engineering works are confined to shallow depths where weathering has a dominant role to play and affects almost all the properties of rocks.

Considerable research efforts have been carried out in an attempt at identifying the impacts of weathering processes (both physical and chemical) on the physical, hydraulic and mechanical properties of weak to medium strong rocks. The key mineral compositions and petrographic features of these rocks are also studied in relation to the environment and duration under which these rocks have been subjected. Several forms of mathematical relationships between these factors have also been derived. Significant understanding on the impact of weathering on the rock has been gained from the research results. These findings are however not directly applicable to the engineering practices specifically to the stability analysis and design of geo engineering structures. Rare attempt has been made at determining the mathematical relation between the weathering,processes and parameters used in the failure or strength criteria of the rock mass has not been made. Such criterion will be useful to predict the stability of geological structures as a function of time, and hence allows implementing an appropriate support system (if needed) to ensure their long-term stability.

1.2 Research objectives

The objective of this research is to experimentally determine the effects of weathering processes on some weak rocks using a large-scaled slake durability testing device. The effort primarily involves simulation of the weathering-induced degradation of rock specimens, determination of the physical and mechanical properties of the rocks at various stages of degradation, and wet and dry slake durability testing. The results from the large-scaled slake durability tests are compared with the results of the conventional durability testing and the weathering simulations. Similarity and discrepancies are discussed. The research findings will be useful for the prediction of the rock degradation under in-situ environment.

1.3 Research methodology

This research consists of six main tasks; literature review, sample collection and preparation, laboratory experiments, mathematical relations, thesis writing and presentation. The work plan is illustrated in the Figure 1.1.

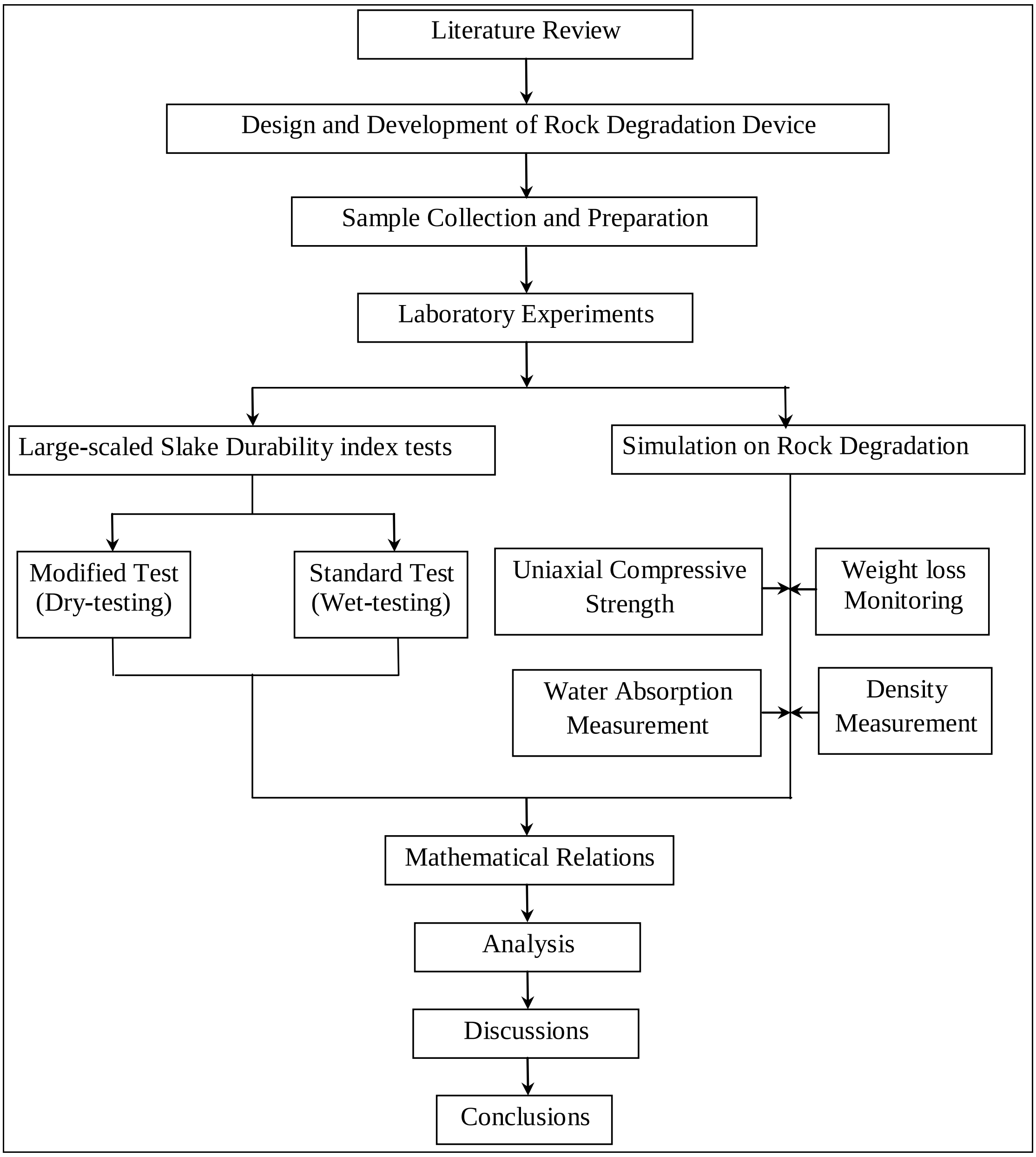

Figure 1.1 Research plan

1.3.1 Literature review

Literature review has been carried out to gain an understanding of the weathering process and the factors affecting strength and durability of rocks**.** The reviewed topics include large-scale slake durability index testing, uniaxial compressive strength testing, weight loss monitoring, density measurements and water absorption measurements. The sources of information are from journals, technical reports and conference papers.

1.3.2 Design and development of rock degradation device

A large-scaled slake durability test device is designed and developed. The new device will accommodate rock fragments with size four times larger than those used in the conventional device.

1.3.3 Sample collection and preparation

Three sandstone types have been collected from the field. Sample preparation is carried out in the laboratory at the Suranaree University of Technology. Preparation of these samples follows the relevant ASTM standard as much as practical.

1.3.4 Laboratory experiments

The laboratory testing is divided into three main groups: large-scale slake durability tests, uniaxial compressive strength tests and measurements of the rock specific gravity and water absorption. The large-scale slake durability test method follows the ASTM (D4644) standard practice. The tests are intended to assess the effect of water on the rate of rock weathering. The uniaxial compressive strength test method follows the ASTM (D7012) standard practice. The tests have been performed to understand the rock degradation under cycles of heating and cooling. The methods of specific gravity and water absorption measurements follow the ASTM (C127).

1.3.5 Mathematical relations

The results from laboratory are used to develop mathematical relations between the weathering parameters and rock properties. The correlations include rock strength, slake durability, weight loss, density, water absorption and degree of rock weathering. All above parameters are calculated as a function of time.

1.3.6 Conclusion and thesis writing

All research activities, methods, and results are documented and compiled in the thesis.

1.4 Scope and limitations of the study

Three sandstone types that are commonly encountered in the east and northeast of Thailand are collected from the field for the laboratory testing. These rocks include Khok Kruat sandstone, Phra Wihan sandstone and Phu Kradung sandstone as they are likely to deteriorate quickly after exposed to atmosphere. The laboratory testing includes large-scale slake durability index testing, uniaxial compressive strength testing, weight loss monitoring, density measurements and water absorption measurements using relevant ASTM standards and ISRM Suggested Method, are followed as much as practical. No in-situ measurement or field testing are performed.

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 preparation. Slake durability index testing and rock degradation simulation are presented in Chapter four. Chapter five shows correlation between large-scaled and standard-scaled slake durability index, as well as the prediction scheme of rock degradation. Chapter six provides the discussions, conclusions, and recommendations for future studies.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter summarizes the results of literature review carried out to improve an understanding of rock degradation by weathering. The topics reviewed here include the factors influencing the rock weathering, laboratory test methods that can be correlated to rock strength.

2.2 Weathering processes

Abramson et al. (1995) state that weathering in general is a group of processes by which surface rock disintegrates into smaller particles or dissolves into water due to the impact of the atmosphere and hydrosphere. The 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.

2.2.1 Physical weathering

Primary minerals and rocks are splitted in fragments due to physical weathering. This leads to environmental conditions that favor chemical weathering. There are several forms of physical weathering (Robison and Williams, 1994), as follows.

Abrasion: Water carrying suspended rock fragments has a scouring action on surfaces. Examples are the grinding action of glaciers, gravel, pebbles and boulders moved along and constantly abraded by fast-flowing streams. Particles carried by wind have a sand-blasting effect.

Wetting and drying: Water penetrates into rocks and reacts with their constituent minerals.

Freezing and thawing: When water is trapped in rock and reacts with constituent minerals.

Thermal expansion and contraction of minerals: Rocks are composed of different kinds of minerals. When heated up by solar radiation each different mineral will expand and contract at a different rate with surface-temperature fluctuations. With time, the stresses produced are sufficient to weaken the bonds along grain boundaries, and thus flaking of fragments.

Pressure unloading or pressure-release jointing: There is a reduction in pressure on a rock due to removal of overlying material. This allows rocks to split along planes of weakness or joints.

Crystallization: In arid environments, water evaporates at the surface of rocks and crystals form from dissolved minerals. Over time, the crystals grow and exert a force great enough to separate mineral grains and break up rocks.

Action of organisms: They aid in the physical disintegration of rocks. Pressures exerted by roots during growth are able to rupture rocks.

2.2.2 Chemical weathering

Moon and Jayawardane (2004) studied the geomechanical and geochemical weathering of Karamu basalt in New Zealand. They concluded that the early stages of weathering as initial fracturing of the rock were physical processes, followed by the progressive development of secondary minerals that reduced the strength of the rocks. From these results, it is apparent 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.

Yokota and Iwamatsu (1999) studied the weathering process of soft pyroclastic rocks in a steep slope. The pyroclastic rocks composing the slopes contain many weakly interlocked volcanic glass and pumice fragments. Their physical properties depend on the degree of welding. A pyroclastic rock is generally similar to sandstone with regard to its engineering properties. In general, the weathering and softening of rocks are attributable to changes not only in the physical and mechanical characteristics, but also in the chemical properties of the rocks. Mechanical changes in these 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. Rock porosity increases and both dry density and strength decrease with time.

2.3 Factors affecting strength and durability of some weak rocks

The mineralogy and the geometric arrangement (microfabric) of particles affect slaking and strength of weak rocks (Engin et al., 1999). For shales, their microfabric includes features of both argillaceous rocks (e.g. mudstones and clay rocks) and fragmental rocks (composed of grains, e. g. sandstones). Therefore, the geomechanical characteristics of shales cannot be determined as easily as for other types of rocks. In order to predict the behavior of shales, one has to understand the effect of both grains and clay minerals on geomechanical properties of rocks (Koncagul and Santi, 1999). These factors are briefly discussed as follows.

Finer grained sediments are more susceptible to breakdown and at higher rates than coarse grained sedimentary materials (D'Appolonia Consulting Engineers, 1980).

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 (D'Appolonia Consulting Engineers, 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. Similarly, stresses will concentrate along grain edges in the uniaxial compression test. However, depending on the degree of bonding between the grains, such angular shaped particles may provide a great deal of interlocking thus increasing the compressive strength. Several researchers (Fahy and Guccions, 1979; Ulusay, et al., 1994; Shakoor and Bonelli, 1991) reported positive correlation between the uniaxial compressive strength and percentage of angular grains. 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). These researchers found a significant positive correlation between these variables and uniaxial compressive strength of sandstone samples. Since sutured contacts provide better interlocking of grains, these types of contacts should increase the hardness and durability of specimens also.

Due to its abundance as a rock forming mineral, most of the correlations established by previous researchers (Fahy and Guccions, 1979; Shakoor and Bonelli, 1991; Gunsallus and Kulhawy, 1984) found a negative relationship between quartz content and uniaxial compressive strength of the investigated sandstones. Handlin and Hager (1957); Bell (1978); Barbour et al. (1979) 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 macrofractures can propagate through the specimen by disrupting the structure and breaking the bonds within the groundmass. Mineralogy of bonding 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.

Bell (1978) correlated 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.

Shale rocks may contain various amounts of clay and non-clay minerals, organic matter, and precipitated salts. Mineralogy is the primary factor controlling the physical and chemical properties of such rocks (Mitchell, 1993). For engineering applications, as a size term, clay refers to all material smaller than 0.002 mm. As a mineral term, it refers to specific clay minerals (e.g. talc, mica, chlorite or smectite). These clay minerals occur in small particle sizes and their unit cells ordinarily have a residual negative charge that is balanced by the adsorption of cations from solution (Mitchell, 1993). The type of clay minerals and availability of cations affect the properties of argillaceous rocks.

Different clay minerals have varying degrees of swelling capability. The order in which swelling potential decreases is : montmorillonite > illite > halloysite > kaolinite. Types of ions existing as dissolved solids in the wetting fluid also strongly affect the degree of swelling. For instance, swelling of montmorillonite decreases as other univalent or divalent ions in following order substitute for sodium (Na) : lithium (Li) > potassium (K) > calcium (Ca) > magnesium (Mg) > hydrogen (H) (Mitchell, 1993). Swelling potential is expected to decrease durability but to have little effect on hardness or strength.

Slaking is the most common physical degradation mechanism affecting clays, clay soils and clay rich rocks. Moriwaki and Mitchell (1977) study various types of slaking and the factors behind them in detail. The investigated variables were clay mineralogy, adsorbed-cation ratios, water content and consolidation-fluid electrolyte concentrations. It is concluded that the type of slaking is strongly controlled by clay mineralogy and the concentration of exchangeable Na-ions. The four common types of slaking in pure clays are dispersion slaking (Na-kaolinite), swelling slaking (Na17 montmorillonite), body slaking (Ca-kaolinite and Ca-illite) and surface slaking (Camontmorillonite). Since clay minerals constitute the dominant portion of shales, the intrinsic rock-slaking behavior will differ based on the amount and type of the constituent clay minerals in shale. Mixtures of various clay minerals will lead to combinations of slaking modes. Some clay minerals may exhibit two different slaking modes following one another (Santi and Koncagul, 1996). Increase of hydration and double layer repulsion force and negative pore pressure are slaking mechanisms common in smectites (D'Appolonia Consulting Engineers, 1980). Their open structure allows the entry of water carrying dissolved ions and leads to great expansion and destruction of the crystal lattice. Dispersed structures are less susceptible to these mechanisms due to their lower permeability. Pore air compression could be a significant slaking mechanism for materials composed of non-swelling clay minerals. None of these mechanisms are directly related to strength or hardness of argillaceous rocks.

In general, experimental literature shows that the greater the water content (w_c), the lower the compressive strength of a specimen. 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 (1966); 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).

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.

Shales with larger pores are more resistant to slaking (Vallejo et al., 1994). This is specifically true for shales composed of kaolinite, which slake as a result of pore air compression breaking up the hydrogen bonds that connect individual plates to one another. Conversely, the larger the pores, the lower the compressive strength (Deere and Miller, 1966), hardness and crushing strength of shale samples under point load (Vallejo et al., 1994). Porosity has a significant effect on mechanical performance. Price (1960); Dube and Singh (1972) report that in sedimentary rocks all strength properties decrease with increasing porosity. The physical explanation of this is that high porosity assists the networking (propagation) of stress induced microfractures (Howarth and Rowlands, 1986). The slake durability index of highly porous argillaceous rocks should also be lower (except those containing kaolinite) due to higher degree of slaking because higher porosity (combined with high permeability) provides a larger surface area open to water interaction.

Although much research has focused on measurement of strength and durability, the number of studies that compared strength and durability predictive tests to microscopic properties is very limited, with almost no studies focusing on weak rocks and especially shales. 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.

Fuenkajorn, K. (2008); Sri-in and Fuenkajorn, K. (2007) studied 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.

2.4 Tests that can be correlated to strength

Simple laboratory tests that can be correlated to compressive strength of intact rocks include uniaxial compressive strength testing, slake durability testing, weight loss measurement, density measurement and water absorption testing. The large slake durability tests are intended to assess the resistance to weathering of shale or other weak or soft rocks samples after being subjected to two standard cycles of drying and wetting (ASTM D4644). In this test dried fragments of rock with known weight are placed in drum fabricated. The drum is rotated in horizontal position along its longitudinal axis while partially submerged in distilled water to promote wetting of the sample. The specimens and the drum are dried at the end of the rotation cycle (10 minutes at 20 rpm) and weighed. After two cycles of rotating and drying the weight loss and the shape and size of the remaining rock fragments are recorded and the slake durability index is calculated. Koncagul and Santi (1999) establish a correlation between the uniaxial compressive strength, the slake durability and shore hardness using mineralogical and intrinsic properties of shale samples (varying degrees of silt and sand contents in Kentucky, USA) to explain the differences between the measured and the predicted results. The results of slake durability index after two cycles range from 30 to 97%. The correlation can be represented by the following equation:

$$UCS = 658(I_{d2}) + 9081 : r = 0.63 \qquad (2.1)$$

where UCS is uniaxial compressive strength (kPa). I_{d2} is the second cycle of slake durability index (%).

Gokceoglu et al. (2000) study the factors affecting the rock durability with an emphasis on the influence of number of drying and wetting cycles of 141 weak rock samples, including schist and sandstone. The samples were subjected to slake durability test and uniaxial compressive test. A relationship between the uniaxial compressive strength and the fourth cycle slake durability index is found only for the marls.

$$UCS = 2.54I_{d4} - 202 : r = 0.76 \qquad (2.2)$$

where UCS is the uniaxial compressive strength (MPa). I_{d4} is the fourth cycle of slake durability index (%).

Uniaxial compressive strength tests have often been determination of the strength of intact rock core specimens in uniaxial compression and confined compression (ASTM D7012). The test method specifies the apparatus, instrumentation, and procedures for determining the stress-axial strain and the stress-lateral strain curves, as well as Young's modulus, *E*, and Poisson's ratio, ν. Tsiambaos and Sabatakakis (2004) study the soft to strong rocks under different conversion factors relating uniaxial compressive and point loading strength. The samples were mainly sedimentary carbonate rocks (limestones, marly limestones, sandstone and marlstone), since this type of sedimentary rocks is the most common one in Greece. The results show the conversion factor between point load and uniaxial compressive strength varies from 13 for soft sedimentary rocks exhibiting a value of $I_{s(50)}<2$ MPa, 20 for medium rocks exhibiting a value of $2<I_{s(50)}<5$ MPa and 28 for hard rocks with value of $I_{s(50)}>5$ MPa.

CHAPTER III

SAMPLE PREPARATION

3.1 Introduction

Rock samples are collected from the sites. This research emphasizes weak rocks. The three sandstones from Khok Kruat, Phra Wihan and Phu Kradung formations are collected. These rocks are commonly found in the northeast of Thailand. They also have significant impacts on long-term stability of many engineering structures constructed in the regions. This chapter describes the mineral compositions of the rock samples and the locations from which they have been obtained.

3.2 Sample collection

Table 3.1 gives rock names, locations from which they have been collected, and formations to which they belong. Rock samples are divided into two main groups. Sample are prepared for the conventional large slake durability test and for simulation under actual in-situ condition. A minimum of ten rock samples are prepared for each test and each rock type. Figure 3.1 shows rock fragments with a nominal size of 4-5 inches prepared for large-scale slake durability index testing. Two sets of the samples are prepared for both sizes; one for dry testing and the other for wet testing. Each set comprises 10 fragments. The rock samples prepared for actual simulations have cylindrical shaped with the diameter of 2 inches and length 2 of inches as shown in Figure 3.2.

3.3 Mineralogical Study

The mineral compositions of the rock samples are determined by using X-ray diffraction method. Table 3.2 gives the results of the X-ray diffraction analysis. 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 3.1 Rock specimens used in this study.

Rock Names	**Code**	**UTM**	**Locations**	**Rock Formation**	**Age**
Khok Kruat sandstone	KKSS	47P0820992/1646362	Khok Kruat district, Nakhon Ratchasima province	Khok Kruat	Upper - Lower Cretaceous
Phu Kradung sandstone	PKSS	47P0758292/1701367	Amphur Thep Sathit, Chaiyaphum privince	Phu Kradung	Lower – Jurassic
Phra Wihan sandstone	PWSS	47P0812102/1598902	Amphur Wang Nam Khieo, Nakhon Ratchasima province	Phra Wihan/	Lower - Jurassic

Table 3.2 Mineral compositions of rock specimens.

Rock Names	**Density (g/cc)**	**Quartz (%)**	**Mica (%)**	**Feldspar (%)**	**Other (%)**	**Cementing**	**Contact**	**Grain Size (mm)**	**Grain Shape**	**Sorting**	**Color**
Khok Kruat sandstone	2.45	72.00	3.00	5.00	20.00	Calcite	grain contact	0.1-1.5	angular	poorly	brownish red
Phu Kradung sandstone	2.59	90.00	2.00	5.00	3.00	Hematite	grain contact	0.1-1.0	angular	moderate	brownish red
Phra Wihan sandstone	2.35	97.00	-	-	3.00	Silica	grain contact	2.00	angular	well	yellow

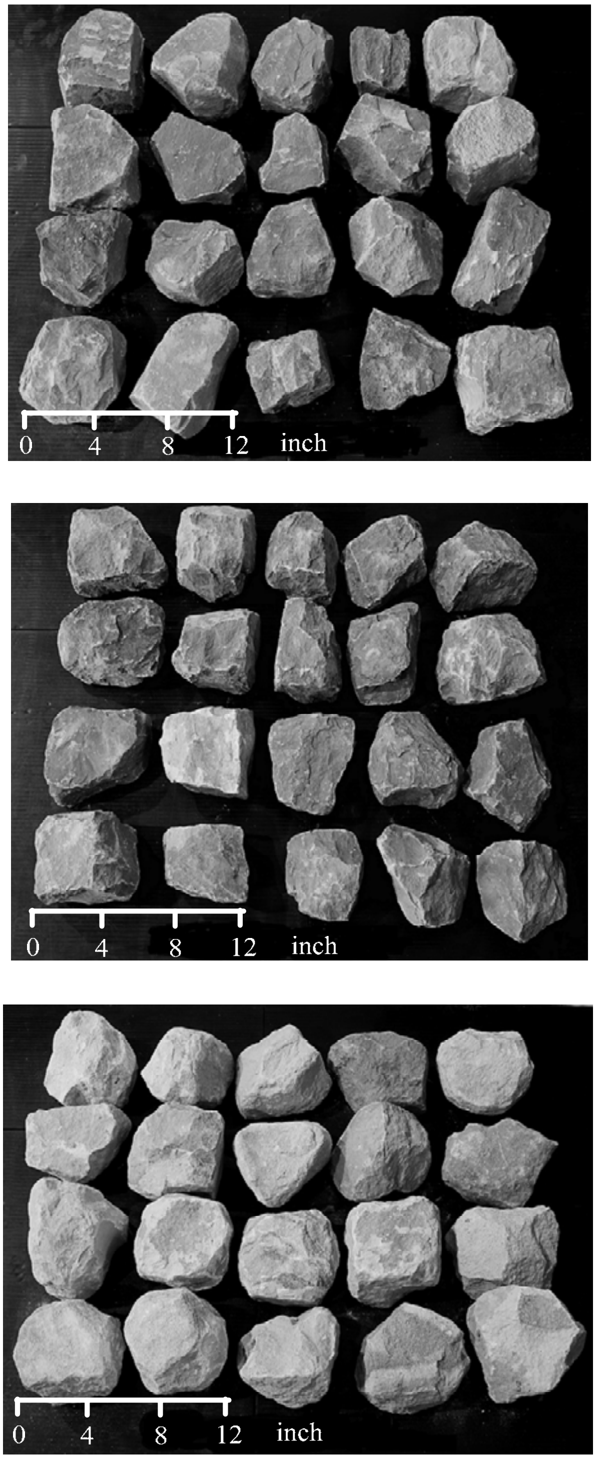

Figure 3.1 Rock samples prepared for large scale slake durability index tests. From top to bottom: Khok Kruat, Phu Kradung and Phra Wihan sandstones

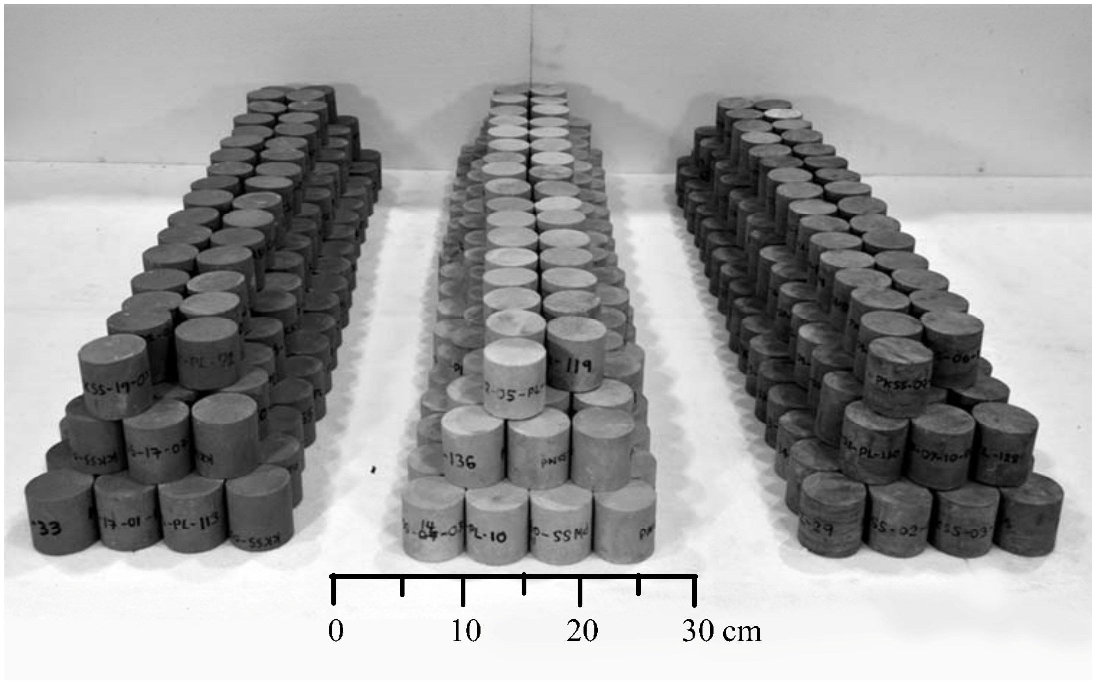

Figure 3.2 Rock samples prepared for simulation of rock degradation.
From left to right: Khok Kruat, Phra Wihan
and Phu Kradung sandstones

Figure 3.3 Rock samples placed under actual conditions

CHAPTER IV

LABORATORY EXPERIMENTS

4.1 Introduction

The laboratory experiments performed can be divided into two main types: large-scale slake durability index testing, and simulation of rock degradation. During the simulation of rock degradation, series of uniaxial compressive strength index tests, weight loss monitoring, and measurements of density and water absorption of the rock specimens are performed. The results are used as indicators of the degrees of rock weathering.

4.2 Large-scaled slake durability index test

The primary objectives of the large-scaled slake durability index test (hereafter called SDI 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 on the rock degradation. Two series of SDI test were performed on two separate sets of rock specimens with similar and comparable characteristics. For the first series, the test procedure, apparatus (Figure 4.1) and data reduction were similar to that of the standard practice (ASTM D4644), except that the tests were performed up to tenth cycles, instead of two cycles as specified by the standard, and that the drum size is larger than the standard one. The second test series was identical to the first one except that no water was in the trough during rotating the drum, i.e., slaking under dry condition. The second test series (hereafter called SDI dry-testing) was carried out to assess the impact of water on the weathering process for each rock type.

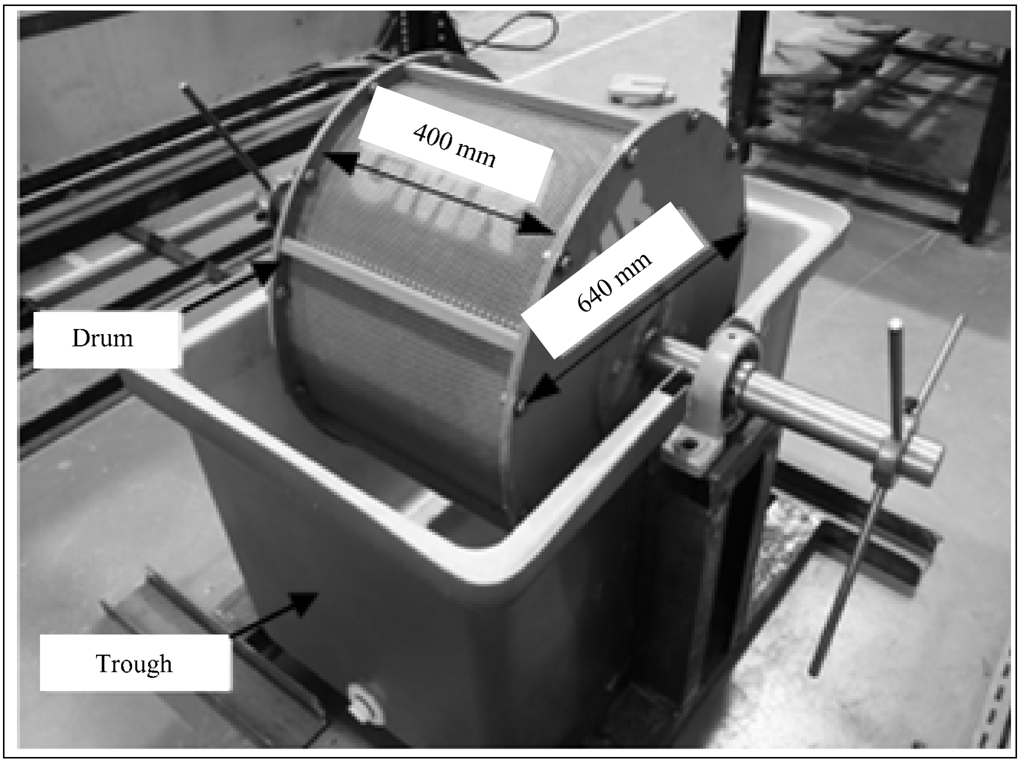

Figure 4.1 Large-scaled slake durability test apparatus.

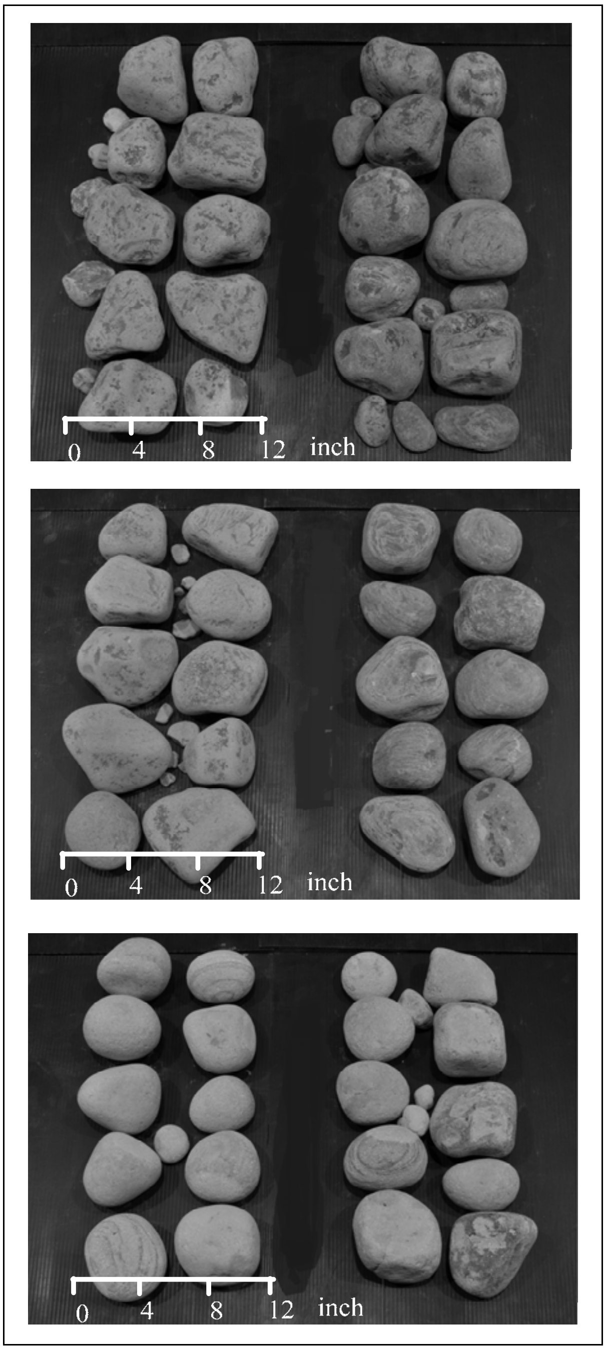

Figure 4.2 Examples of post-test specimens from for large-scaled slake durability index tests. From top to bottom: Khok Kruat, Phu Kradung and Phra Wihan sandstones

4.2.1 Test results

The SDI values for all rock types are plotted as a function of number of cycles (N) for testing with water in the trough in Figure 4.3, and without water in the trough (dry condition) in Figure 4.4. Tables 4.1 and 4.2 list the SDI values obtained for each test cycle. For wet and dry testing, Phra Wihan sandstone tends to degrade much quicker than do other rock types probably. The most durable rocks seem to be Phu Kradung sandstone. The three rock types are classified based on Gamble (1971) classification, as shown in Table 4.3.

Comparisons between wet and dry testing suggests that the impacts of water on rate of rock degradation varied among different rock types. Figures 4.5 and 4.6 compare SDI obtained from wet and dry testing after the first and the tenth cycles. Three sandstones are sensitive to water in terms of their durability. The rates of SDI reduction for wet testing are greater than those for dry testing. At the end of cycle 10 the SDI values for wet testing are considerably lower than those for dry testing for all sandstones. Khok Kruat sandstone shows the greatest water-sensitivity than the other two.

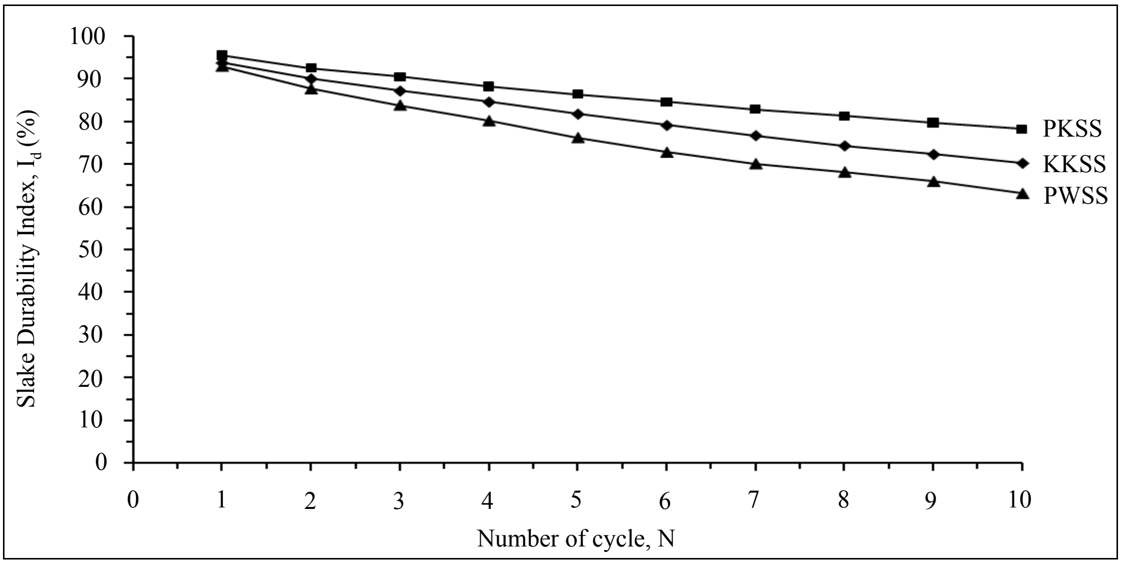

Figure 4.3 Slake durability index for 10 cycles with water in trough.

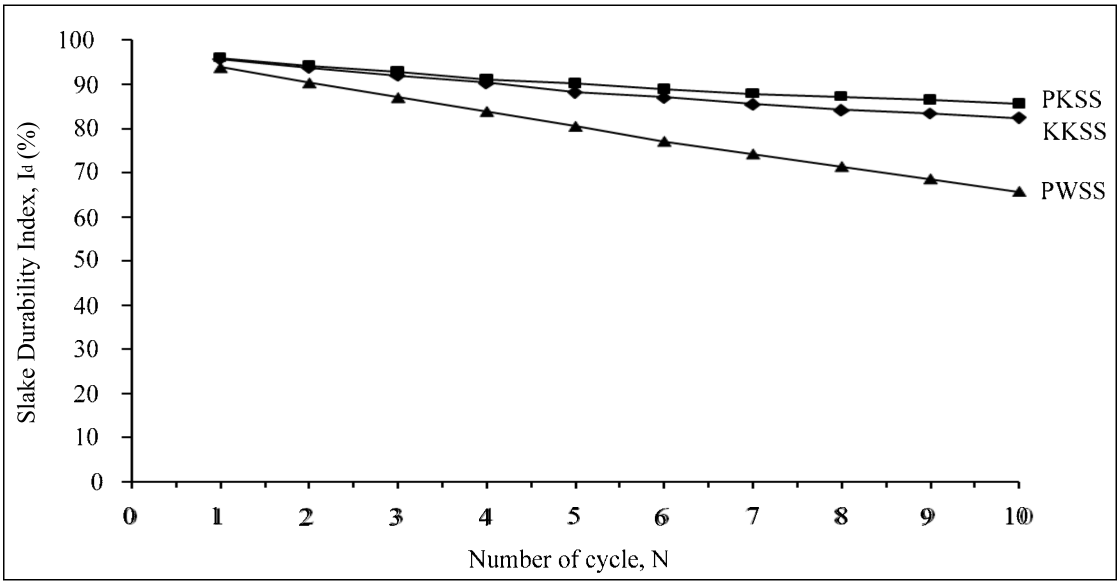

Figure 4.4 Slake durability index for 10 cycles without water in trough.

Table 4.1 Slake durability index test results with water in trough.

Rock Name	Slake Durability Index, I_d (%)									
	Number of Cycles									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
KKSS	93.68	89.98	87.13	84.54	81.72	79.07	76.70	74.29	72.28	70.22
PKSS	95.42	92.44	90.39	88.16	86.30	84.49	82.79	81.21	79.63	78.15
PWSS	92.84	87.57	83.77	80.14	76.17	72.76	70.10	68.18	65.96	63.14

Table 4.2 Slake durability index test results without water in trough.

Rock Name	Slake Durability Index, I_d (%)									
	Number of Cycles									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
KKSS	95.60	93.67	91.92	90.23	88.10	86.94	85.41	84.11	83.31	82.39
PKSS	96.01	94.27	92.89	91.20	90.23	88.93	87.94	87.28	86.49	85.68
PWSS	93.87	90.38	87.05	83.88	80.49	77.08	74.23	71.36	68.55	65.70

Table 4.3 Slake durability index of rock samples based on Gamble's classification (ISRM, 1981).

Rock Name	$I_{d(1)}$ (%)	$I_{d(2)}$ (%)
KKSS	medium durability	medium high durability
PKSS	medium high durability	medium high durability
PWSS	low durability	medium durability

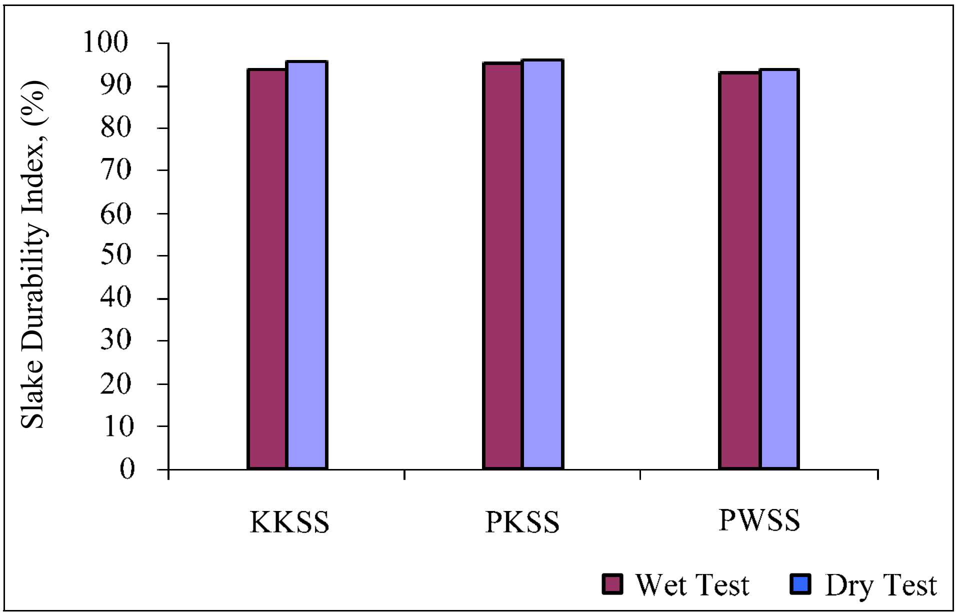

Figure 4.5 Comparison between SDI wet and dry test results after the first cycle.

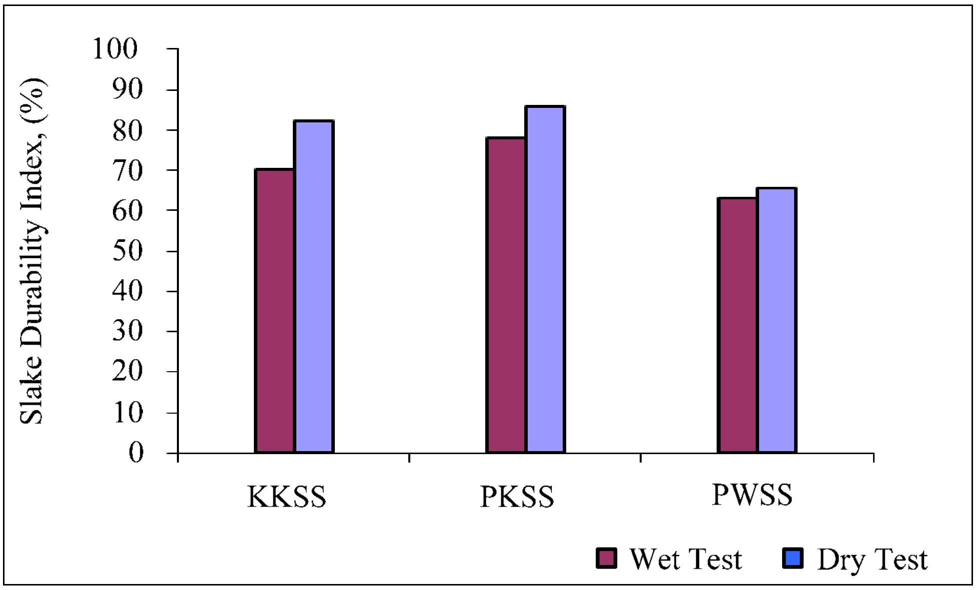

Figure 4.6 Comparison between SDI wet and dry test results after the tenth cycle.

4.2.2 Implications of SDI for long-term durability

An attempt is made here to project the results of SDI testing toward the future conditions of the rocks. Sri-in and Fuenkajorn, K. (2007) proposed a concept to describe the physical characteristics of the rock fragments used in the SDI test. It is assumed that all rock fragments inside the drum for each test are identical. Figure 4.7 shows two different types of the rates of degradation (weight loss) during SDI testing. The first type shows linear decreases of the SDI as the number of test cycles increases (Figure 4.7 – left). This implies that each rock fragment in the drum has relatively uniform texture (uniform degree of weathering, hardness or strength) from the inner matrix to the outer surface. The lower the strength of rock fragment, the higher the rate of degradation.

For the second type (Figure 4.7 – right) each rock fragment inside the drum has non-uniform texture. The outer surface is weaker (lower strength, higher degree of weathering or more sensitive to water) than the inner matrix. This is reflected by the decrease of the rate of degradation as the test cycles increase, the curves for samples D, E and F concave upward. Here the decrease of rock matrix strength from the outer surface to the inner part can be abrupt or grading, depending on rock type and weathering characteristics. The more abrupt the change, the more concave the SDI - N curve. It is believed that weathering characteristics of most rocks follow the second type, because the SDI - N curves obtained here and from elsewhere tend to be concave, more or less, upward.

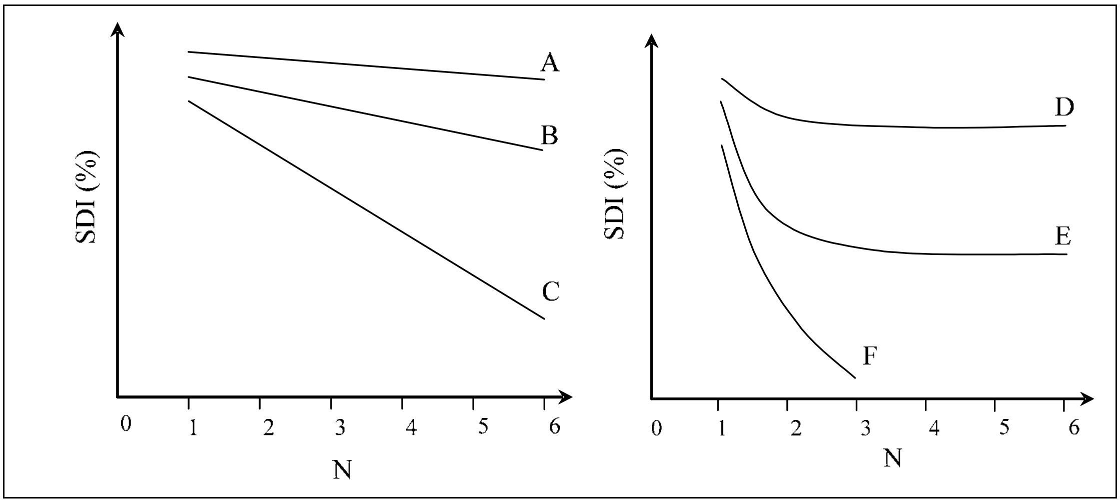

Figure 4.7 Proposed concept of rock degradation during SDI testing. Samples A, B and C (on the left) have uniform texture. Samples D, E and F (on the right) have weathered zone overall a stronger (fresher) inner part. (Sri-in and Fuenkajorn, K., 2007)

4.2.3 Projection of rock durability

Let us assume here that the proposed hypothesis of the second type of weathering is valid. It can be postulated that rock fragments inside the drum tend to get stronger as they are subjected to a greater number of SDI test cycles. When the rock fragments become stronger, the difference of the SDI values between the adjacent cycles (hereafter called ΔSDI) will also get smaller. ΔSDI at any cycle can be represented by:

$$\Delta SDI = SDI\,(N) - SDI\,(N+1) \tag{4.1}$$

where SDI (N) is the slake durability index at cycle N, and SDI (N+1) is the slake durability index at cycle N+1.

In order to predict the rock durability in the future, the ΔSDI are calculated for the ten cycles. Figure 4.8 plots ΔSDI of sedimentary rocks as a function of number of cycles counted backward. This backward cycle is denoted by N*, primarily to avoid confusing with the original forward cycles (N) defined earlier. This backward plotting is mainly for a convenience of analyzing the test results. For this new approach, while ΔSDI increases with N*, the rock becomes weaker. This is similar to the actual rock degradation due to weathering process that has occurred in the in-situ condition. For the results obtained above the ΔSDI that represents the difference between the SDI of the first cycle and the conditions as collected (before subjecting to the first cycle) is plotted in cycle number, N* = 10. Therefore the difference between the SDI values of the ninth and tenth cycles is plotted for N* = 1.

The ΔSDI – N* curves have a significant advantage over the conventional SDI – N diagram. The new curves can show a future trend for the rock durability, as ΔSDI values can be statistically projected to a larger number of test cycles beyond those performed in the laboratory. As an example, the ΔSDI is projected to N* = 60 cycles in Figure 4.8. Regression analyses on the 10 ΔSDI values indicate that an exponential equation can best describe the variation of ΔSDI with N*. The implications of N* and actual time or duration under which the rock is subject to actual in-situ conditions is very difficult to define, if at all possible. More discussions on this issue are given in the following chapter. Table 4.4 gives results of regression analysis on the empirical relation between ΔSDI and N* for all rock types.

4.2.4 Classification of rock durability

A new classification system is proposed for rock durability based on ΔSDI and its projected values to any N*, as shown in Table 4.5. The ΔSDI – N* curves obtained from three rock types tested here are compared against the new classification system (Figure 4.8). For example, at N* = 60 or below, Khok Kruat, Phra Wihan and Phu Kradung are classified as moderate durability rock. This agrees with the classification and conclusions drawn earlier from the results of wet and dry SDI test. It should be noted that the projection of ΔSDI – N* curves relies heavily on the number of cycles actually tested. A larger the number of tested cycles will result in a higher reliability of the projected results.

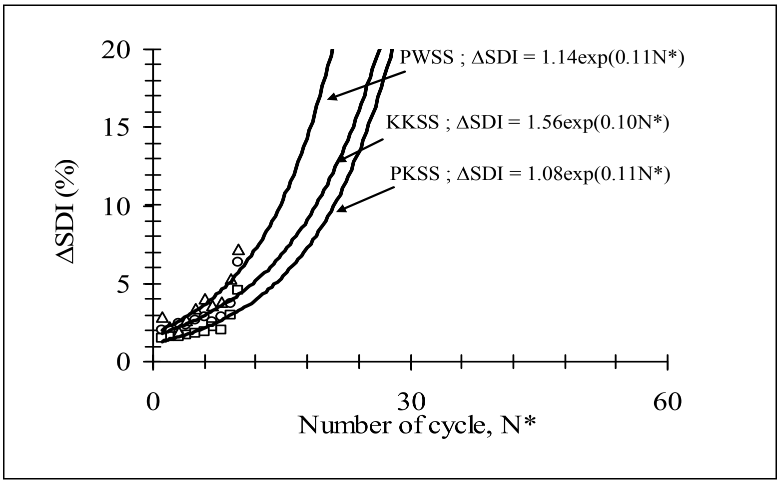

Figure 4.8 ΔSDI as a function of N^*. Rock conditions as collected are plotted at cycle no. 10.

Table 4.4 Empirical constants for an exponential relationship between ΔSDI and N*.

Rock Types	**ΔSDI = A • exp(B • N^*)**		**Correlation Coefficient**
	A	**B**	
KKSS	1.56	0.10	0.85
PWSS	1.08	0.11	0.88
PKSS	1.14	0.11	0.92

Table 4.5 Proposed classification system for durability of intact rocks.

(Sri-in and Fuenkajorn, K., 2007)

Description	**ΔSDI (%)**
Very high durability	< 1
High durability	1-3
Modulate durability	3-7
Low durability	7-15
Very low durability	> 15

4.3 Simulation of rock degradation

4.3.1 Laboratory simulation methods

The objective of the simulation of rock degradation is to experimentally assess the degrees of rock weathering as it is subjected to the cyclic changes of temperatures and humidity. One hundred rocks cylindrical shaped were prepared from three rock types. The specimens were placed in an oven at 105 Celsius for 12 hours and rapidly submerged in a tank of water at 25 Celsius for 12 hours. This rapid heating and cooling process was repeated 200 times (200 days). Uniaxial compressive strength tests, weight loss, water absorption, and density measurement of the specimens were monitored at every 20 cycles. The test procedures follow the ASTM (D7012) and ASTM (C127) standard practice. These physical and mechanical property parameters are used as indicators of rock degradation. Correlation between these parameters will also be carried out in an attempt to determine the mathematical relationship between the weathering parameters and rock properties calculated as a function of time.

4.3.2 Actual environment

Fifty rocks cylindrical shaped were prepared from three rock types. The specimens were placed outdoor under actual in-situ condition. Uniaxial compressive strength tests, weight loss, water absorption, and density measurement of the specimens were monitored at every 120 days.

4.3.3 Uniaxial compressive strength tests

The uniaxial compressive strength tests were performed on all rock types, using two sets of specimens. The first set is prepared from the laboratory simulation. The second set is from actual in-situ condition in site. The uniaxial compressive strength tests is performed by using compression machine model SBEL PLT-75 which is capable of applying axial load up to 350 kN (Figure 4.9). Figure 4.10 shows post-test specimens from the uniaxial compressive strength tests. Table 4.6 gives the results from laboratory simulation and the results from actual in-situ condition in site in Table 4.7. The figure 4.11 shows compressive strength as a function of test cycle. Actual environment (left) and laboratory simulation test (right). The strength of Khok Kruat sandstone, Phu Kradung sandstone and Phra Wihan sandstone are decrease with increasing heating and cooling cycles.

The tangent elastic moduli at 50% failure stress have been calculated from the measured stress-strain curves obtained from uniaxial compressive testing. The elastic modulus a function of test cycle is shown in Figure 4.12.

4.3.4 Weight loss monitoring and density measurement

The results show that Khok Kruat sandstone has a higher rate of weight loss than the other rocks because the high amount of mica contents (Table 3.2) makes the rock disintegrate easily. Its fragments therefore become extremely brittle and weaker when they are subjected to rapid changing of temperatures. Phu Kradung sandstone and Phra Wihan sandstone have the lowest rate of weight loss because those are crystallized forming rocks. This is the effect of chemical weathering rather than physical weathering. Figure 4.13 shows weight loss as a function of test cycle. Actual environment (left) and laboratory simulation test (right).

Density calculated from the mass per unit volume of a material, expressed as kilograms per cubic metre (pounds per cubic foot). The results show in Figure 4.14

4.3.5 Water absorption

The results show that Phra Wihan sandstone has a higher rate of water absorption than other rocks in laboratory simulation. In actual environment Khok Kruat sandstone has a higher rate of water absorption than other rocks. The both results are shown in Figure 4.15.

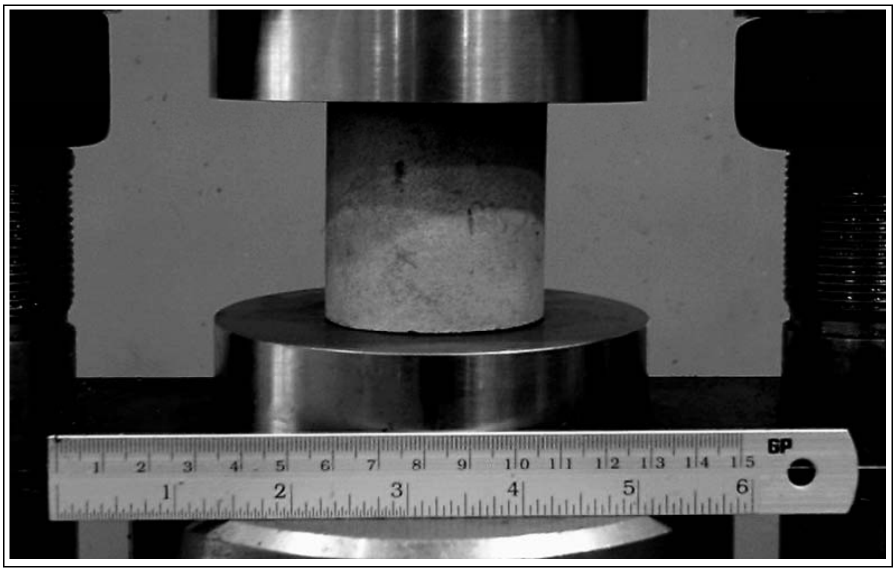

Figure 4.9 Uniaxial compressive strength test apparatus

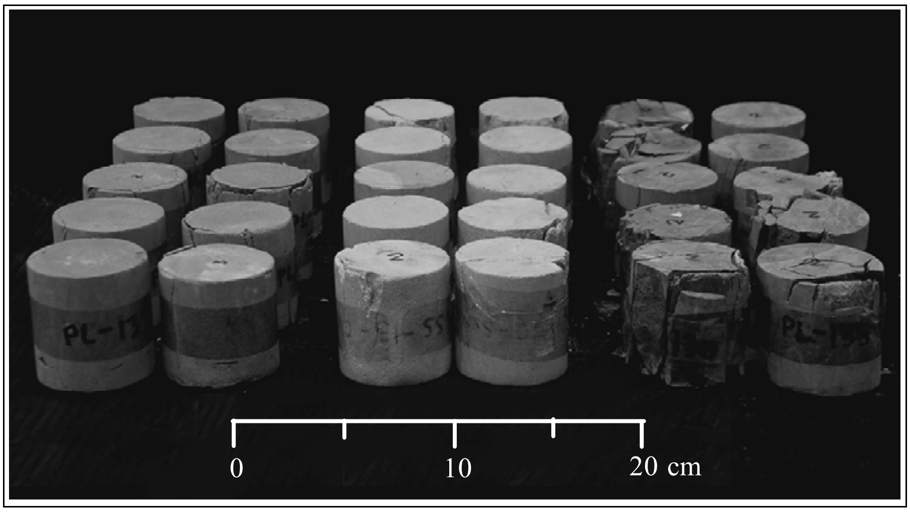

Figure 4.10 Examples of post-test specimens from the uniaxial compressive strength test.

Table 4.6 Results of uniaxial compressive strength test from laboratory simulation.

Rock Name	**Uniaxial compressive strength (MPa)**									
	Number of Cycles									
	20	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**
KKSS	67.50	49.92	42.46	39.36	37.16	37.3	36.8	34.3	33.3	34.1
PKSS	84.10	64.89	62.91	57.60	54.10	52.6	52.1	51.8	51.0	49.0
PWSS	66.80	47.57	41.49	37.06	35.89	33.5	32.5	30.1	29.9	29.4

Table 4.7 Results of uniaxial compressive strength test from actual in-situ condition.

Rock Name	**Uniaxial compressive strength (MPa)**				
	Days				
	0	**120**	**240**	**360**	**480**
KKSS	67.50	45.09	40.52	38.90	35.90
PKSS	84.10	72.44	64.16	56.20	51.00
PWSS	66.8	42.45	37.46	36.2	35.6

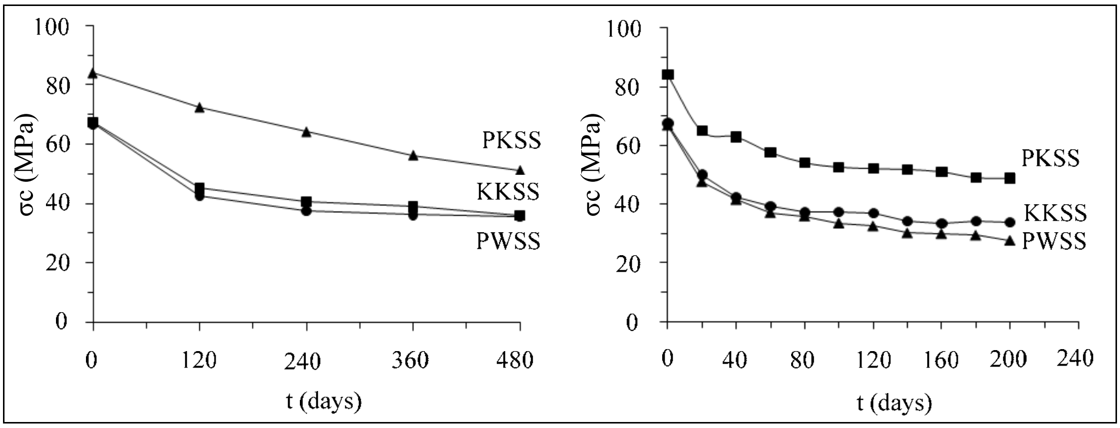

Figure 4.11 Compressive strength as a function of test cycle. Actual environment (left). Simulation test (right)

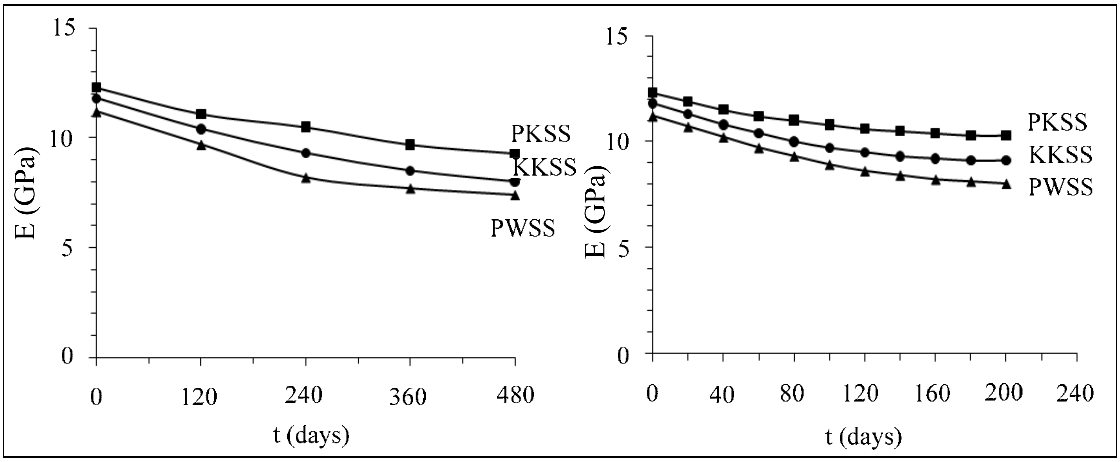

Figure 4.12 Elastic modulus as a function of test cycle. Actual environment (left). Simulation test (right)

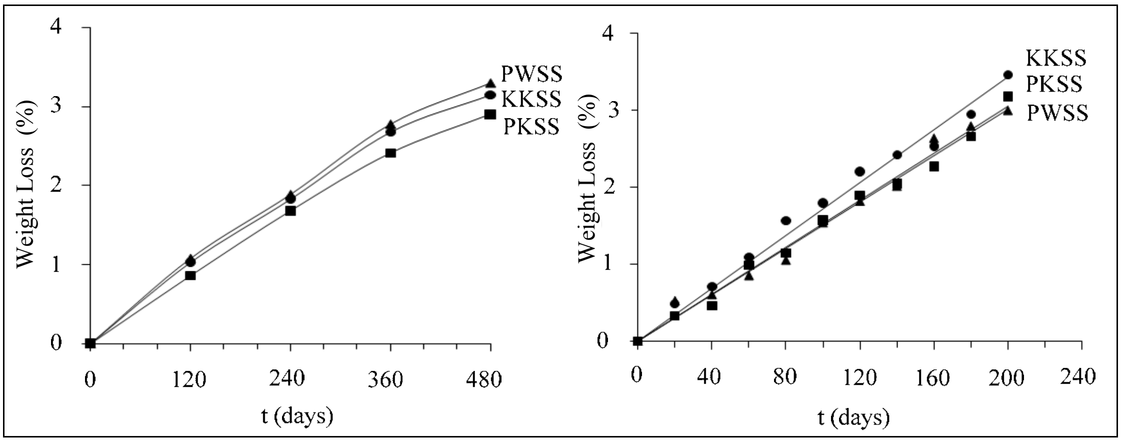

Figure 4.13 Weight loss as a function of test cycle. Actual environment (left). Simulation test (right)

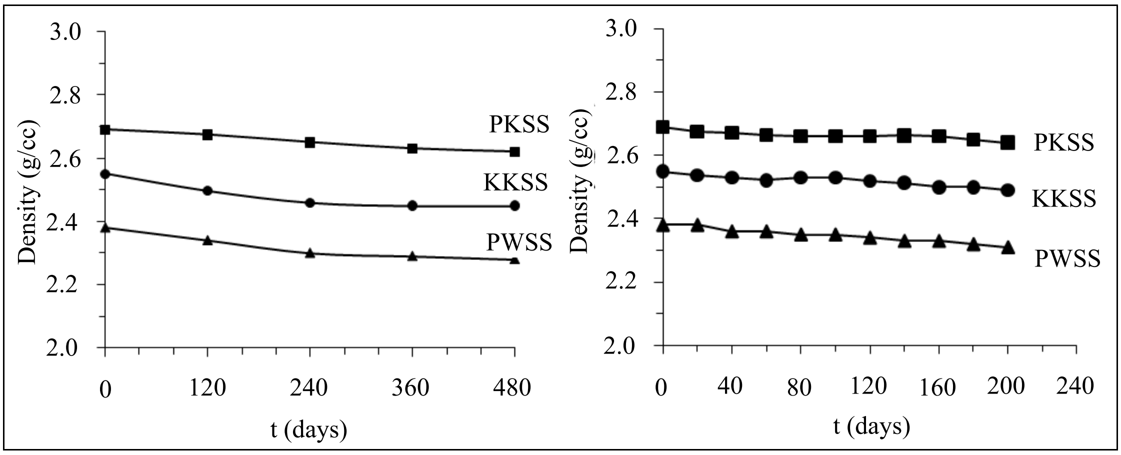

Figure 4.14 Density as a function of test cycle. Actual environment (left). Simulation test (right)

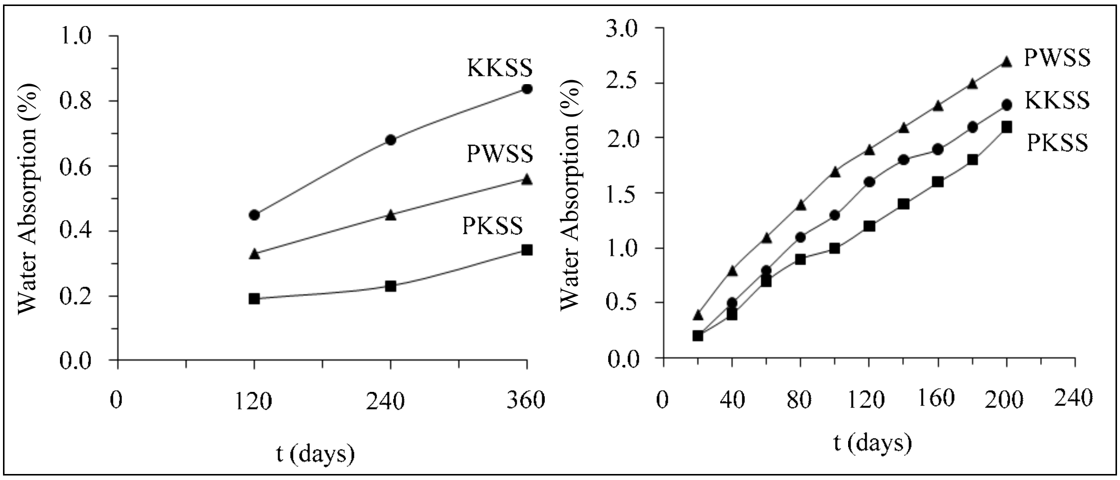

Figure 4.15 Water absorption as a function of test cycle. Actual environment (left). Simulation test (right)

CHAPTER V

CORRELATION BETWEEN LARGE-SCALED AND STANDARD-SCALED SLAKE DURABILITY INDEX

5.1 Introduction

The objective of this chapter is to compare the result of the large-scaled and standard-scaled slake durability index testing. A concept of heat energy absorption is used to compare the degradation simulation with the actual in- situ condition, as a function of time. The degradation can therefore be predicted as a function of time.

5.2 Relationship between large-scaled and standard-scaled slake durability index testing

The slake durability index test (SDI) as a function of the test cycle (N) are compared with the large-scaled with the standard-scaled results. The greater reduction of the SDI values is obtained for the large-scaled testing, as compared to the standard scaled testing (Figure 5.1). The results are compared with those obtained from the ASTM standard testing to assess the size effect of rock fragments on the results. The results indicate that the large-scaled test results tend to represent the rock deterioration better than do the small-scaled results.

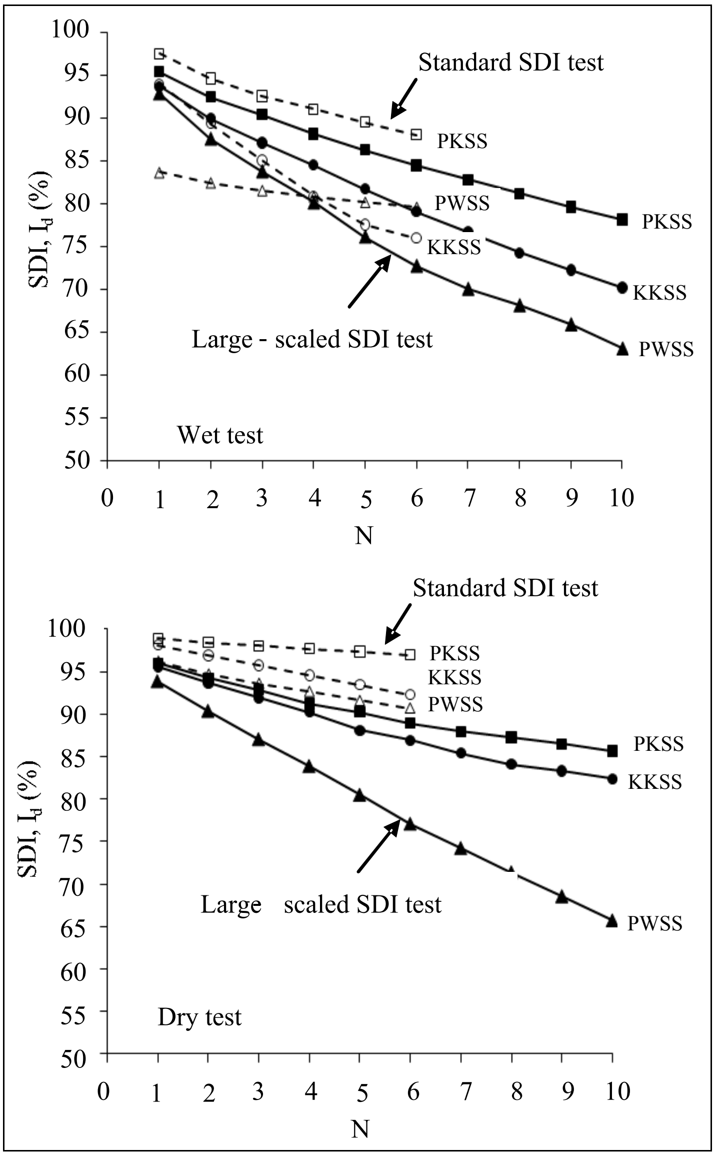

Figure 5.1 Results of SDI tests: wet testing (top) and dry testing (bottom).

5.3 Correlation between simulation and actual in-situ condition

An attempt is made here to correlate the simulation cycles with the actual in-situ condition. An easy and relatively conservative approach is to use the concept of energy adsorption. The amount of heat energy that has been applied to the rock specimens during the degradation simulation is compared with that actual environment. Figure 5.2 shows the temperature change imposed on the rock during one cycle of degradation simulation. The Thai Meteorological Department (2004) has monitored the temperature change during the days throughout the year in the area of Nakhon Ratchsima province. Figure 5.3 shows the daily temperature changes averaged for the year 2004. The heat energy absorbed by the rock can be calculated by using an equation (Richard et al., 1998),

$$Q = \sum^{n} \left(m \cdot C_p \cdot \Delta T_i \cdot \Delta t_i \right) \tag{5.2}$$

where Q is the absorbed energy of rock specimen (kJ), m is the weight of rock specimen (kg), C_p is the specific heat capacity (kJ/kg•K), ΔT_i is the temperature change in Kelvin, t_i is time interval of energy absorption (hours) and n is number of hours. The coefficient of heat capacity of most rocks varies between 0.6 and 1.2 kJ/kg•K with an average value of 0.90 kJ/kg•K (Figure 5.4).

From equation (5.2), the absorbed energy during heating simulation of most rocks is estimated as 12.960 MJ•hr (where m = 15 kg, C_p = 0.90 kJ/kg•K, ΔT = 80 K, t = 12 hrs).

For the actual in- situ condition, the absorbed energy in one day is estimated as 0.735 MJ•hr (where m = 15 kg, C_p = 0.90 kJ/kg•K, ΔT is temperature change in each one hour as shown in Figure 5.2, t = 16 hrs.). Therefore, one simulation cycle of heating and cooling approximately equals to 18 days under in-situ condition (12.960/0.735 = 17.63). Therefore, n can be correlated with time.

$$n \approx 18 \text{ days} \tag{5.3}$$

where n is the cycle of heating and cooling simulation. The above correlation, equation (5.3), is considered extremely conservative because the temperature changes for the simulation are much more abrupt than those actually occurring under in-situ conditions. Since the applied energy in one day during the simulation is the same as that used in the SDI test, N* can be related to time, as follows.

$$N^* \approx 18 \text{ days} \tag{5.4}$$

From equation (5.4) ΔSDI for each rock type can be plotted as a function of time (in days) in Figure 5.5.

5.4 Predict the rock strength as a function of time.

From figure 5.6, the uniaxial compressive strength test of the rock can be correlated with time. The mathematic relations of rock strength as a function of time are developed. The strength index can therefore be correlated to the uniaxial compressive strength of the rock by using the following relation.

$$y = mx + c_0 \tag{5.5}$$

where y is strength, m is slope, c is basic strength and x is time. The rock compressive strength in the prediction the rock strength can be defined in terms of uniaxial compressive strength, and number of days (t)

For Khok Kruat sandstone,

$$\sigma_{c,o} = 1.48\ \sigma_{c,s} \tag{5.6}$$

For Phu Kradung sandstone,

$$\sigma_{c,o} = 1.78\ \sigma_{c,s} \tag{5.7}$$

For Phra Wihan sandstone,

$$\sigma_{c,o} = 2.06\ \sigma_{c,s} \tag{5.8}$$

The results indicate that effect of uniaxial compressive strength as predict by the actual environment are more appropriate when compared with the laboratory simulation test.

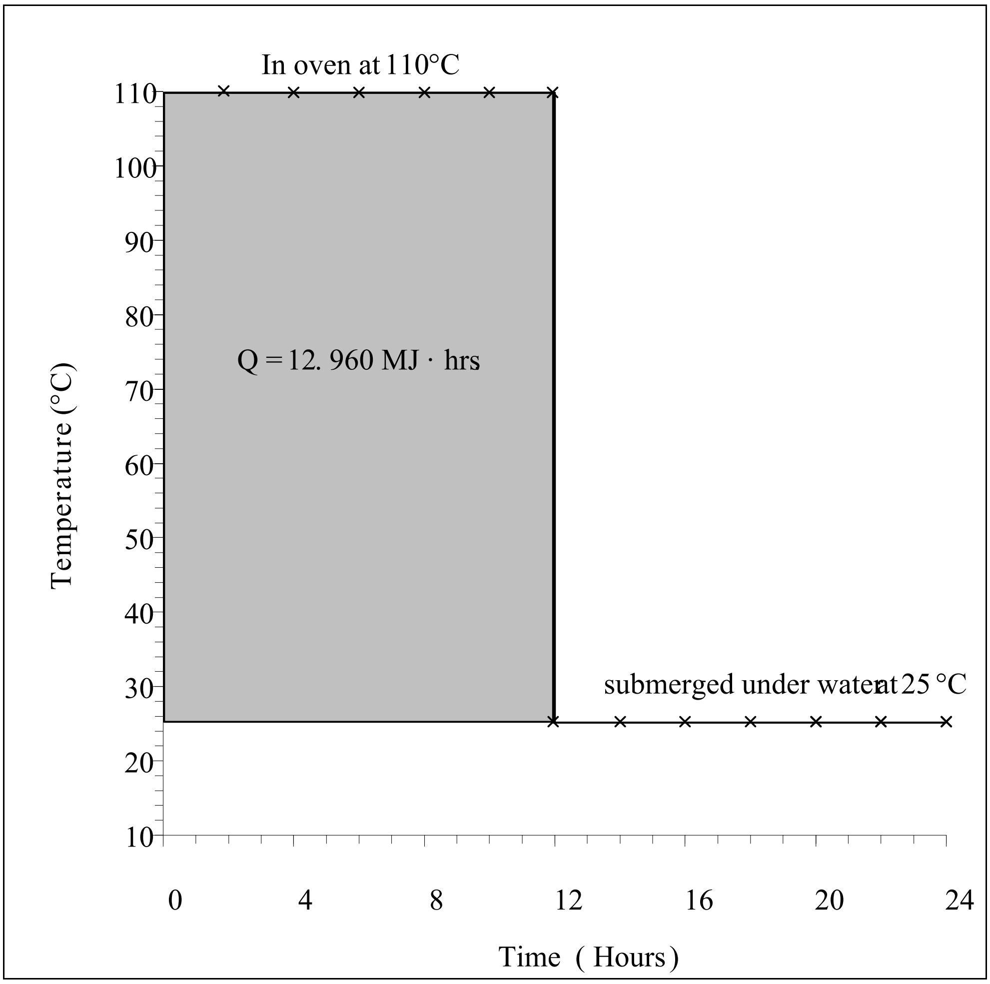

Figure 5.2 Variation of temperatures for one cycle of heating and cooling simulation in laboratory.

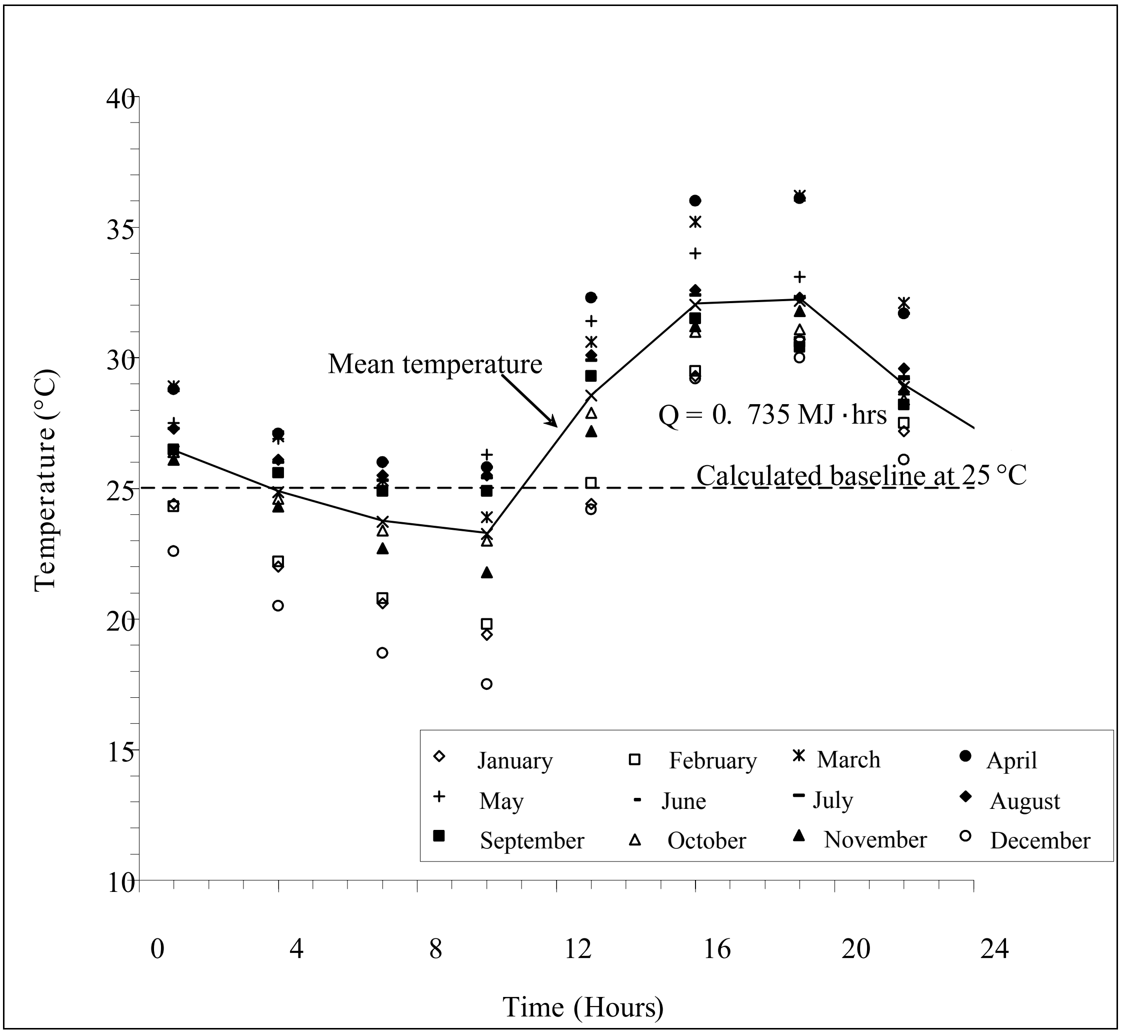

Figure 5.3 Variation of daily temperatures in the Nakhon Ratehasima province (Thai Meteorological Department, 2004). The line indicates average daily temperature change in the year 2004.

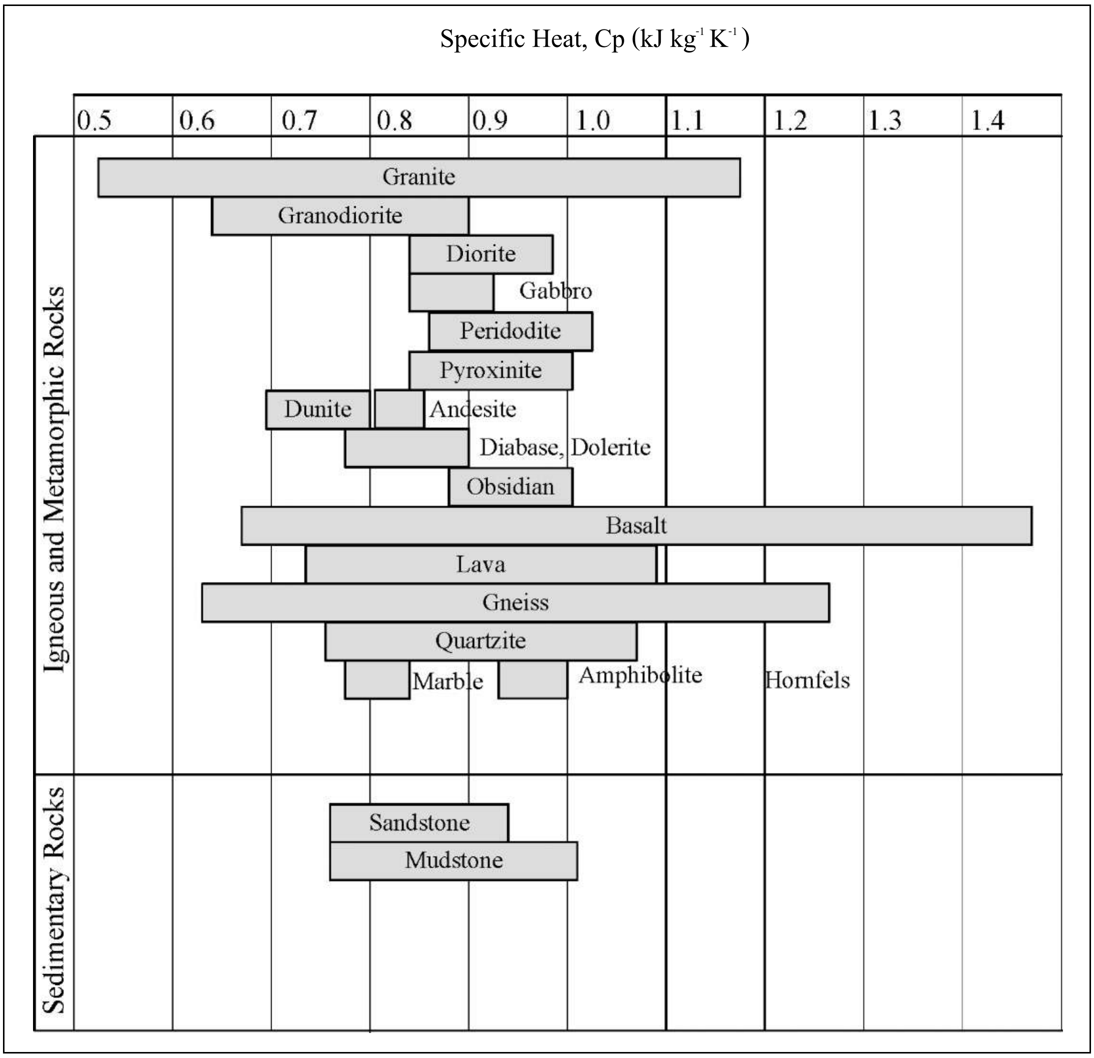

Figure 5.4 Comparison of coefficients of heat capacity of various rock types (Modified from Department Angewandte Geowissenschaften and Geophysik, 2006).

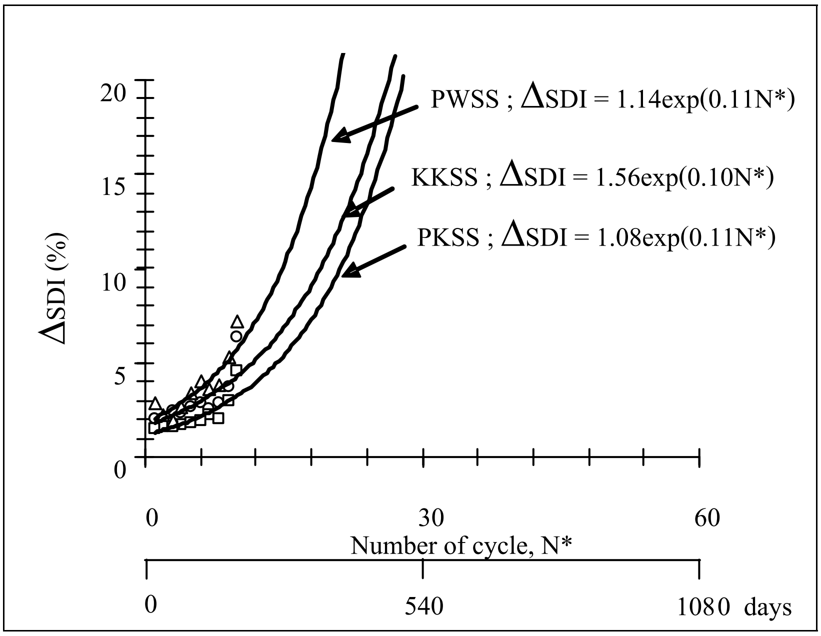

Figure 5.5 ΔSDI as a function of time under in-situ condition.

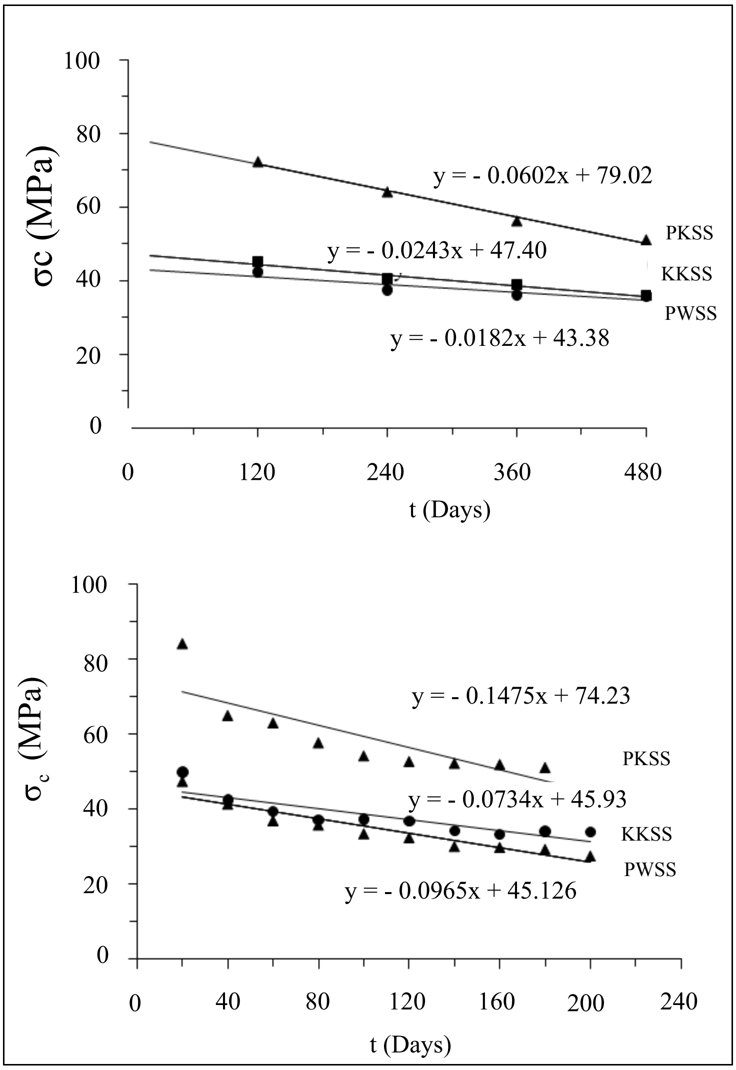

Figure 5.6 Uniaxial compressive strength as a function of t. Actual environment (top). Laboratory Simulation test (bottom).

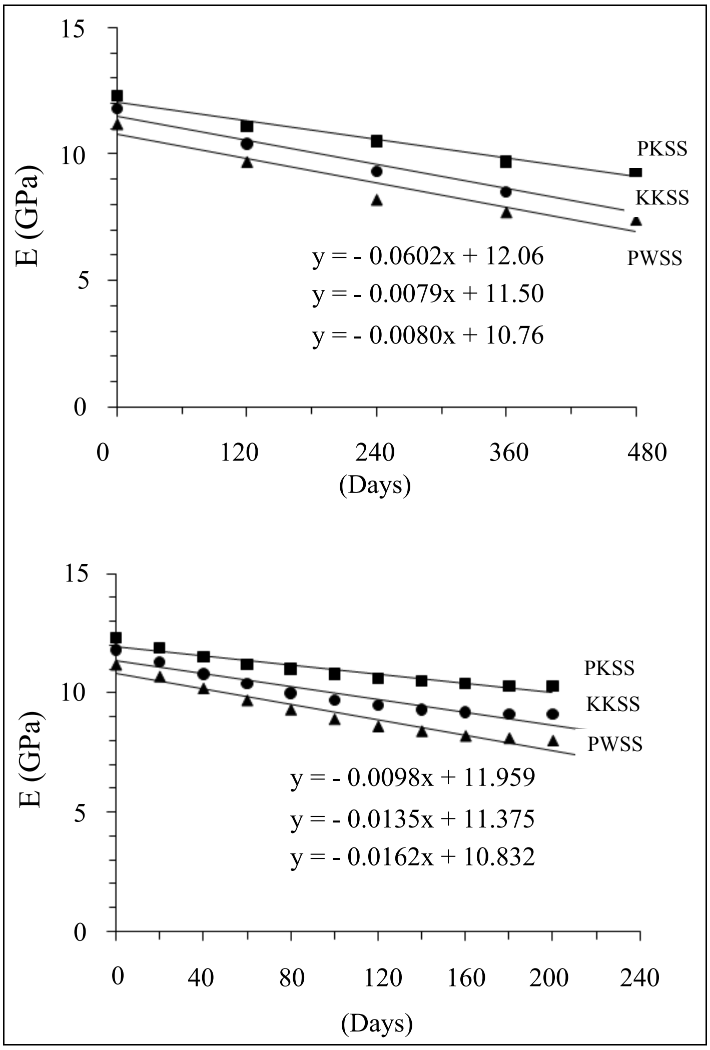

Figure 5.7 Elastic modulus as a function of t. Actual environment (top). Laboratory Simulation test (bottom).

CHAPTER VI

DISCUSSIONS, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

6.1 Discussions and conclusions

The objective of this research is to determine the effects of weathering processes on some weak rocks using a large-scaled slake durability testing device. The effort primarily involves simulation of the weathering-induced degradation of rock specimens, determination of the physical and mechanical properties of the rocks at various stages of degradation, and wet and dry slake durability testing.

Large-scaled slake durability index testing has been performed on Khok Kruat, Phu Kradung and Phra Wihan sandstones. The results are compared with those obtained from the ASTM standard testing to assess the size effect of rock fragments on the results. The results indicate that the large-scaled test results tend to represent the rock deterioration better than do the small-scaled results. All tested sandstones show a greater percentage of weight loss when they are tested with large rock fragments compared to the small rock fragments. This is probably due the greater energy imposed for the large-scaled testing that for the standard-scale test. All tested sandstones are sensitive to water. Khok Kruat sandstone shows the greatest water-sensitivity than the other two.

The prediction of ΔSDI value as a function of N* is obtained by extrapolation of the fitted curve to a higher number of N*. The reliability of the prediction largely depends on the number of cycles during the SDI test. This issue is of concern particularly for the rock with high gradient of ΔSDI values which are normally obtained for low to very low durability rocks. A larger number of test cycles (probably 20 or more) would be required to provide a more reliable prediction. However, the ΔSDI values obtained for medium to very high durability rocks tend to have a linear relation with N*. For these rocks, the number of SDI test cycles between 5 and 10 would be sufficient.

The approach to relate the simulation cycles with the actual time in the field by using the heat energy absorption concept is very conservative because it considers only the temperature difference and duration, not the rate change of temperatures. It is believed that the rapid change of temperature during the simulation would impose more damage on the rock fabric than does the gradual change occurred under in-situ condition.

6.2 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.

A more diverse rock types, compositions and textures is 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.

More SDI test cycles should be performed to obtain a more accurate projection of the ΔSDI-N* curve, probably up to 20 cycles.

A new or better approach should be sought to correlate the simulation cycles with the actual time. An alternative is to compare the results of rocks under simulated condition in the laboratory with those actually subjected to the in-situ environment. Such approach requires a long-term investigation program.

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APPENDIX A

TECHNICAL PUBLICATION

TECHNICAL PUBLICATION

Rintrawilai, S., Walsri, C., and Fuenkajorn, K. (2010). **Large-scaled slake durability index testing.** In Proceeding Third Thailand Rock Mechanics Symposium. Phetchaburi, Thailand, 10-11 March 2011.

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Large-scaled slake durability index testing

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Keywords: Slake durability, weathering, sandstone, water absorption

ABSTRACT: Large-scaled slake durability index testing has been performed on Khok Kruat, Phu Kradung and Phra Wihan sandstones. The results are compared with those obtained from the ASTM standard testing to assess the size effect of rock fragments on the results. A rotating drum with a diameter of 64 cm and length of 40 cm is fabricated to accommodate ten 4-5 in rock fragments. Both large-scaled and standard-scaled tests are performed under dry and wet conditions for up to 6 cycles (for standard-scaled) and 10 cycles (for large-scaled). The results indicate that the large-scaled test results tend to predict the rock deterioration better than the smalle-scaled results do, primarily due to the greater energy imposed to the rock fragments. All tested sandstones show a greater weight loss when they are tested with large rock fragments compared to the small rock fragments. This allows a better correlation with the actual in-situ conditions. All tested sandstones are sensitive to water. Khok Kruat sandstone shows the greatest water-sensitivity than do the other two.

1 INTRODUCTION

Slake durability index test has long been used to identify the durability and water sensitivity of rocks as subject to engineering requirements under in-situ conditions. The test has been widely accepted and standardized by the American Society for Testing and Materials (ASTM) in 1987 (ASTM D4644), and included as part of the ISRM suggested methods by the International Society for Rock Mechanics in 1981. Several investigators have utilized this method with a common goal of correlating the rock durability, and sometimes strength, with the chemical or mineral compositions and the state of weathering (e.g. Dhakal et al., 2002; Fang & Harrison, 2001; Gokceoglu et al., 2000; Koncagul & Santi 1999; Oguchi & Matsukura, 1999; Oyama & Chigira, M., 1999; Phienwej & Singh, 2005; Tugrul, 2004). One remaining question is how good the test results obtained from small fragment samples (1.5 in) can represent the natural process of rock degradation in the field. Even though considerable amount of researches relevant to rock durability and weathering effects have been conducted, an attempt at investigating the size effects of the tested rock fragments has never been attempted.

The primary objective of this study is to investigate the weathering and degradation characteristics of some intact sandstones by performing large-scaled slake durability index testing. The results are compared with those obtained from the ASTM standard method. An attempt at predicting the rock strength degradation with time is also made. The results can be useful for the design and analysis of rock foundations, embankments, and support system for long-term mechanical stability (i.e. by explicitly considering rock degradation in the design parameters).

2 ROCK SAMPLES

The sandstones selected for testing belong to three sandstone members; including Khok Kruat, Phu Kradung and Phra Wihan sandstones (hereafter called KKSS, PKSS and PWSS). They are classified as weak to medium strong rocks, and are likely to deteriorate quickly after exposed to atmosphere. These rocks are commonly found in the northeast of Thailand. The rock fragments with a nominal sizes of 1.5 in (for standard testing) and of 4-5 in (for large-scaled testing) are prepared for testing. Two sets of the samples are collected for both sizes; one for dry testing and the other for wet testing. Each set comprises 10 fragments. Figure 1 shows the rock fragments prepared for testing. Comparisons of the test results obtained from the two different sizes and under different test conditions will reveal the size effect on the rock deterioration and the water sensitivity of the sandstones.

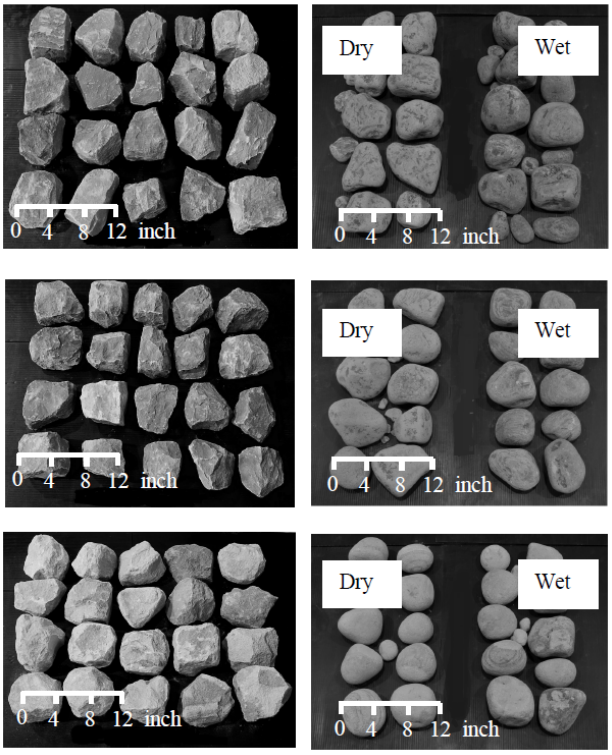

Figure 1. Rock samples before testing (left) and after testing (right). From top to bottom: Khok Kruat, Phu Kradung and Phra Wihan sandstone.

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3 LARGE-SCALE SLAKE DURABILITY DEVICE

A large-scaled slake durability device has been fabricated. It is similar to the ASTM standard device accept that the rotating drum is enlarged to the size of 640 mm in diameter and 400 mm long (Figure 2). It is about 4.5 times larger than the drum size specified by the standard. The mesh opening around the drum is 6 mm. The drum can accommodate 10 rock fragments with a nominal size of 4-5 inches. It is secured on a steel frame and can be freely rotated in the trough. Note that the standard sized drum specified by ASTM (D4644) has a diameter of 140 mm, 100 mm in length with the mesh openings of 2 mm.

4 TEST METHOD

For the 1.5-in rock fragments, two series of SDI test were performed on two separate sets of rock specimens with similar and comparable characteristics. For the first series, the test procedure and data reduction were similar to that of the standard practice (ASTM D4644), except that the tests were performed up to ten cycles (6 cycles or 6 days), instead of two cycles as specified by the standard. This was primarily to establish a longer trend of weight loss as the rock continued to subject to more cycles of scrubbing in the drum. Temperature of the water in the trough is 25 Celsius. The drum were turned 20 rounds per minute for 10 minutes. The second test series was identical to the first one except that no water in the trough during rotating the drum, i.e., slaking under dried condition. The second test series (hereafter called SDI dry-testing) was carried out to assess the impact of water on the weathering process for each rock type. The dry-testing specimens were also placed in the oven for 24 hours for each cycle. The weight loss calculation for both wet and dry testing followed the ASTM (D4644) standard practice.

Similar to the 1.5-in fragments, the 4-in rock fragments were also tested for two series using the large-scaled testing drum. The testing was performed on two separate sets of rock specimens that had similar and comparable characteristics; the first set for dry condition, and the second set for wet condition. Ten cycles of testing were performed for both wet and dry condition. For each cycle, the drum were turned 20 rounds per minute for 10 minutes. Figure 1 shows the rock fragments after testing.

Figure 2. Drum constructed for large-scale slake durability test.

5 TEST RESULTS

Figure 3 shows the SDI as a function of the test cycle (N) and compares the large-scaled with the standard scaled results. The greater reduction of the SDI values is obtained for the large-scaled testing, as compared to the standard scaled testing. This is primarily due to the greater energy imposed to the large rock fragments.

It seems that all tested sandstones are sensitive to water. The rates of SDI reduction for wet testing are greater than those for dry testing. At the end of cycle 10 the SDI values for wet testing are clearly lower than those for dry testing for all sandstones (Figure 4). Khok Kruat sandstone shows the greatest water-sensitivity than do the other two.

Figure 5 shows the water absorbtion as a function of test cycle (N). They are measured from the rock fragments used in the wet testing. The ability to absorb water of the sandstone fragments reduces as the test cycle increases. This implies that before testing the outter matrix of the rock fragments has been weathered more than the inner portion. As the test cycle increases the scrubing process slowly removes the outter matrix and exposes the fresher inner matrix to the testing environment.

6 PREDICTIONS OF ROCK DURABILITY

An attempt is made here to correlate the simulation cycles with the actual in situ condition. The concept proposed by Sri-in & Fuenkajorn (2007) is adopted here. They state that an easy and relatively conservative approach to compare rock deterioration under different states is to use the concept of energy adsorption. The amount of heat energy that has been applied to the rock specimens during the degradation simulation is compared with those actually monitored in the field throughout the year (Thai Meteorological Department 2004). The heat energy absorbed by the rock can be calculated by using the following equation (Richard et al. 1998).

$$Q = \Sigma_{i=1,n} \{m \cdot C_p \cdot \Delta T_i \cdot \Delta t_i\} \qquad (1)$$

where Q is the absorbed energy of the rock specimen (kJ), m is the mass of rock specimen (kg), Cp is the specific heat capacity (kJ/kg K), ΔT_i is the temperature change in Kelvin degrees, Δt_i is the time interval of energy absorption (hours) and n is the number of hours. The coefficient of heat capacity of most rocks varies between 0.6 and 1.2 kJ/kg K with an average value of 0.90 kJ/kg K. In the above equation, the absorbed energy during heating simulation of most rocks is estimated as 12.960 MJ h (where m = 15 kg, C_p = 0.90 kJ/kg K, ΔT = 80 K, t = 12 h). For the in situ condition, the absorbed energy in 1 day is estimated as 0.735 MJ h (where m = 15 kg, C_p = 0.90 kJ/kg K, ΔT is temperature change in each hour, t = 16 h.). Therefore, one simulation cycle of heating and cooling approximately equals 18 days under in situ conditions (12.96/0.735 = 17.63). Therefore, n can be correlated with time, as n & 18 days. This correlation is considered conservative because the temperature changes for the simulation are much more abrupt than those actually occurring under in situ conditions. As the applied energy in 1 day during the simulation is the same as that used in the SDI test, N* can be related to time, as N* & 18 days. The ΔSDI for each rock type shown in Figure 6 can therefore be calculated as a function of time.

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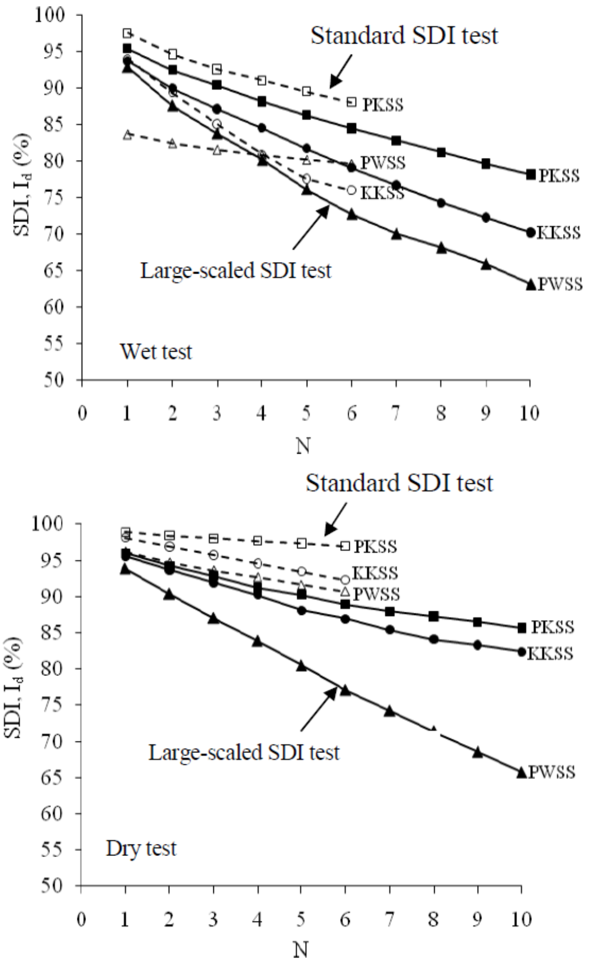

Figure 3. Results of SDI tests: wet testing (top) and dry testing (bottom).

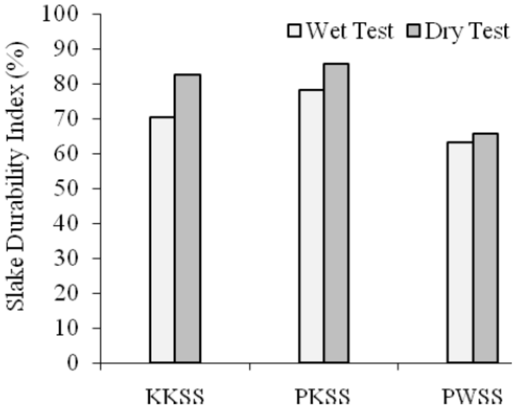

Figure 4. SDI at cycle no.10 for wet and dry testing.

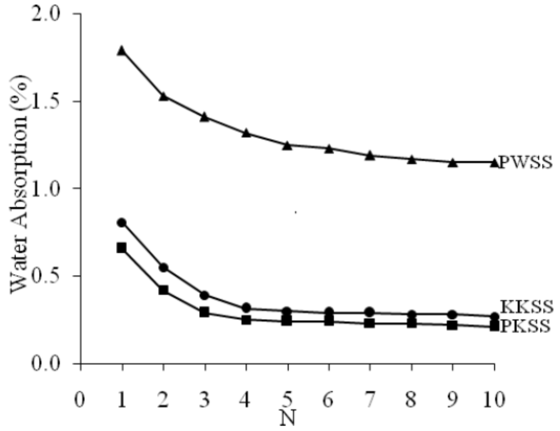

Figure 5. Water absorption as a function of test cycle.

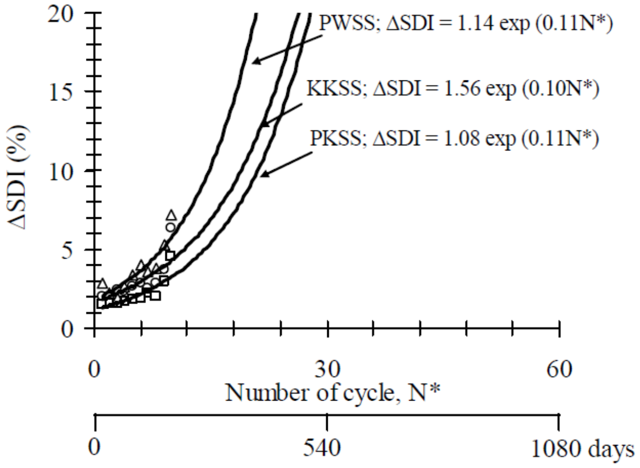

Figure 6. ΔSDI as a function of N^*. Rock conditions as collected are plotted at cycle no. 10.

7 DISCUSSIONS AND CONCLUSIONS

Large-scaled slake durability index testing has been performed on Khok Kruat, Phu Kradung and Phra Wihan sandstones. The results are compared with those obtained from the ASTM standard testing to assess the size effect of rock fragments on the results. The results indicate that the large-scaled test results tend to represent the rock deterioration better than do the smalle-scaled results. All tested sandstones show a greater percentage of weight loss when they are tested with large rock fragments compared to the small rock fragments. This is probably due the greater energy imposed for the large-scaled testing that for the standard-scale test. All tested sandstones are sensitive to water. Khok Kruat sandstone shows the greatest water-sensitivity than the other two.

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Ms. Sukanda Rintrawilai was born on January 21, 1984 in Bangkok province, Thailand. She received her Bachelor’s Degree in Engineering (Geotechnology) from Suranaree University of Technology in 2007. For her post-graduate, she continued to study with a Master’s degree in the Geological Engineering Program, Institute of Engineering, Suranaree university of Technology. During graduation, 2008-2010, she was a part time worker in position of research assistant at the Geomechanics Research Unit, Institute of Engineering, Suranaree University of Technology. She has published one technical papers related to rock mechanics, titled **“Large-Scaled Slake Durability index Testing”** published in the Proceeding of Third Thailand Rock Mechanics Symposium, Phetchaburi, Thailand.