Prediction of Long-Term Strength of Some Weak Rocks

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Abstract

A series of slake durability tests, point load strength index tests, tilt tests and x-ray diffraction analyses were carried out on thirteen rock types, in an attempt to correlating the rock durability with their strengths 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 Pichit pumice breccia, Phra Wihan siltstone, Phu Kradung sandstone, Khok Kruat sandstone and Chonburi schist are classified as low to very low durability rocks, primarily due to the kaolinite content. Nam Duk slaty-shale is considered high durability, not sensitive to water, but is easily disintegrated by rapid change of surrounding temperatures. The point load strength index decreases with an increasing 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.

1. Introduction

A slake durability index test has long been used to identify the durability and water sensitivity of rocks subject to engineering requirements under in situ conditions. The test has been widely accepted and standardised by the American Society for Testing and Materials [1], and included as part of the methods suggested by the International Society for Rock Mechanics since 1981. Several investigators have utilised 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 [2-10]. It has been found that the compressive strength of rocks tends to increase linearly with the slake durability index. Tugrul [9] and Sousa et al. [11] draw conclusions from their experiments that factors affecting rock strength and durability may include mineral compositions, microstructure (size, shape, and geometry of grains), degrees of alteration (bonding, density, and porosity) and texture. Finer grained sediments are more susceptible to breakdown and withstand higher uniaxial compressive loads than do coarse grained sedimentary materials. The uniaxial compressive strength and slake durability index of specimens tend to increase with an increasing packing density, while porosity increases with a decreasing density. Gupta and Seshagiri [12] found that the tangent modulus and compressive strength of some crystalline rocks systematically decrease with increasing weathering state, and that the mode of rock failure is also influenced by the weathering extent into rocks. Even though a considerable amount of research relevant to rock durability and weathering effects has been conducted, attempts at explicitly predicting long-term durability or strength of the rocks as affected by the weathering process under in situ conditions have been rare.

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The primary objective of this research is to study the weathering and degradation characteristics of intact rocks and to predict the rock strength as affected by the weathering process. The main tasks involve: 1) determination of mineral compositions using the X-ray diffraction method, 2) performing of a series of slake durability index testing, 3) simulation of rock degradation by rapid heating and cooling, determination of intact rock strengths at various stages of degradation and 4) the derivation of a mathematical relation between the rock strength and the rate of degradation. This research is part of a mission with an ultimate goal to predict the decrease of rock strength over time due to the weathering processes. The research finding can be of useful for the design and analysis of rock foundations, embankments, and the support system for long-term mechanical stability (i.e. by explicitly considering rock degradation in the design parameters).

2. Rock Samples

Thirteen rock types were selected for this research. They were divided into three main groups: two volcanic rocks, three metamorphic rocks, and eight sedimentary rocks. These rocks represent the exposed outcrops that are commonly found in the east and northeast of Thailand. They also have significant impacts on long-term stability of many engineering structures in the regions (e.g. embankments and foundations of highways, railways and reservoirs, dam abutments, and tunnels). The main mineral compositions of these rocks obtained from X-ray diffraction analyses are given in Tables 1 through 3 for the volcanic, metamorphic, and sedimentary rock groups, respectively. These compositions can assist in explaining the differences in the rock durability under the test conditions performed here, discussed later in the following sections.

3. Slake Durability Test

3.1 Test Method

The primary objectives of the slake durability index (hereafter called SDI) test are to predict long-term durability of the rock specimens, to establish weathering and

Table 1 Mineral compositions of rock specimens in volcanic rock group

Mineral Compositions	Pichit crystal tuff (PCT)	Pichit pumice breccia (PPB)
Quartz (%)	70.8	82.0
Pyrite (%)	8.4	1.9
Kaolinite (%)	3.1	9.3
Calcite (%)	17.7	-
Laumontite (%)	-	6.8
Density (g/cc)	2.58	2.50
Colour	dark gray	white, pink and gray

Table 2 Mineral compositions of rock specimens in metamorphic rock group

Mineral Compositions	KSch	CSch	NDSh
Quartz (%)	43.49	24.80	50.85
Muscovite (%)	6.43	4.94	15.36
Biotite (%)	-	26.86	25.42
Feldspar (%)	12.85	-	-
Kaolinite (%)	-	17.57	-
Chlorite (%)	22.76	-	-
Albite (%)	13.43	-	-
Chamosite (%)	14.47	-	-
Fluoronyboite (%)	-	-	8.37
Density (g/cc)	2.60	2.60	2.59
Colour	grayish green	yellow-brown	brownish gray

Note: KSch - Kanchanaburi schist
CSch - Chonburi schist
NDSh - Nam Duk slaty shale

Table 3 Mineral compositions of rock specimens in sedimentary rock group

Mineral Compositions	MSMD	PWST	NPST	KKST	KKSS	PKSS1	PKSS2	PWSS
Quartz (%)	39.7	72.0	62.0	58.4	72.0	80.0	90.0	97.0
Mica (%)	13.2	9.0	-	22.6	3.0	-	2.0	-
Feldspar (%)	-	5.0	-	12.2	5.0	-	5.0	-
Kaolinite (%)	30.9	-	-	6.5	-	-	-	-
Calcite (%)	-	-	5.0	-	-	-	-	-
Halite (%)	9.1	-	-	-		-	-	-
Other (%)	7.1	20.0	33.0	-	20.0	20.0	3.0	3.0
Density (g/cc)	2.66	2.35	2.59	2.62	2.45	2.29	2.59	2.35
Cementing	-	Hematite	Hematite	-	Calcite	Silica	Hematite	Silica
Contact	-	matrix support	grain support	-	grain support	grain support	grain support	grain support
Grain size (mm)	-	0.1-1.5	0.1-1.0	-	0.1-1.5	1.5-2.0	0.1-1.0	2.0
Grain shape	-	angular	angular	-	angular	angular	angular	angular
Shorting	-	poorly	poorly	-	poorly	well	moderate	well
Colour	reddish brown	brownish red	brownish red	brownish yellow	brownish red	white	brownish red	yellow

Note: MSMD – Maha Sarakham mud stone
PWST – Phra Wihan siltstone
NPST – Nam Phong sandy siltstone
KKST – Kaeng Krachan siltstone
KKSS – Khok Kruat sandstone
PKSS1 – Phu Kradung white sandstone
PKSS2 – Phu Kradung red sandstone
PWSS – Phra Wihan sandstone

degradation characteristics of each rock type, and to assess the impact of water on the rock degradation. Two series of the 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 [1], except that the tests were performed up to six cycles (6 days), instead of two cycles as specified by the standard. This was primarily to establish a longer trend of weight loss as the rocks continued to be subject to more cycles of scrubbing in the drum. The temperature of the water in the trough was 25°C. The second test series was identical to the first one except that there was no water in the trough during the rotating of the drum, i.e., slaking under dry conditions. The second test series 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 at 110°C for 24 hrs for each cycle. The weight loss calculation for both wet and dry testing followed the standard practice [1].

3.2 Test Results

The SDI results are plotted as a function of the number of cycles (N) for testing with water in the trough in Figure 1 and for testing under dry conditions in Figure 2. The SDI of the rock specimens decreased at different rates. For wet testing, Phra Wihan siltstone, Phu Kradung sandstone, and Chonburi schist tend to degrade much quicker than do other rock types because they contain high percentages of kaolinite in the rock matrix. The most durable rocks seems to be Pichit crystal tuff, Nam Phong sandy-siltstone, Nam Duk slaty-shale, and

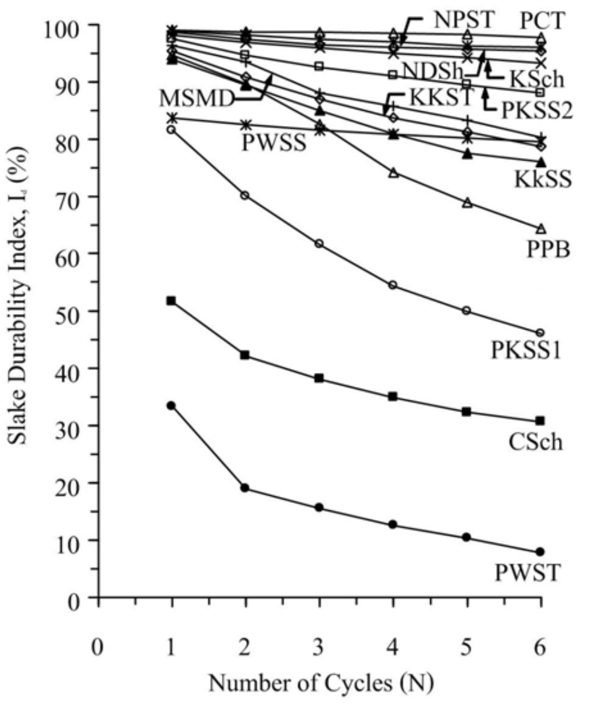

Figure 1 Slake durability index for 6 cycles with water in trough

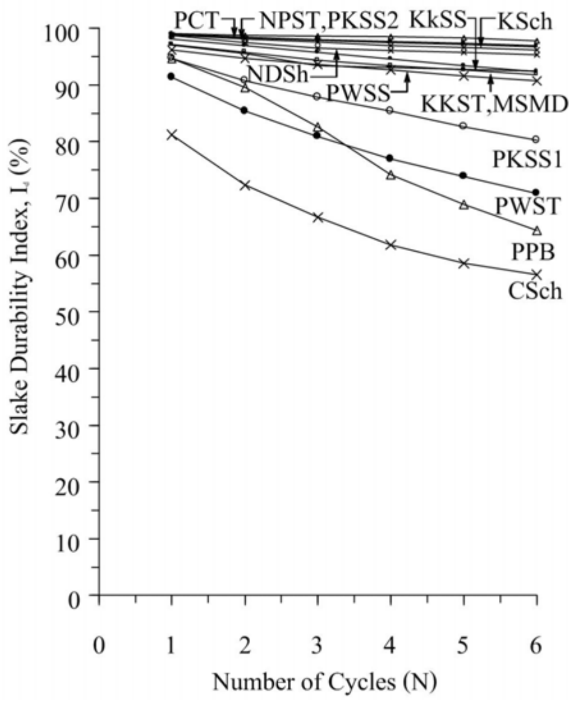

Figure 2 Slake durability index for 6 cycles without water in trough

Kanchanaburi schist. These rocks are considered to have very high durability based on Gamble's classification [13]. Note that the SDI values obtained for Phu Kradung red sandstone and Phra Wihan siltstone also agree with those obtained by Phienwej and Singh [10].

Comparison between wet and dry testing results suggests that the impact of water on the rate of rock degradation varied among different rock types. Figure 3 compare the SDI obtained from wet and dry testing for the sixth cycles. Phra Wihan siltstone, Phu Kradung white sandstone, Pichit pumice breccia, and Chonburi schist are highly sensitive to water in terms of their durability. In other words, without being subjected to water these rocks are still considered moderately durable. For some highly durable rocks (e.g. Pichit crystal tuff, Nam Phong sandy-siltstone, Nam Duk slaty-shale, and Kanchanaburi schist), the SDI values obtained from wet and dry testing are not much different, which implies that water has little impact on their degradation rates.

4. Implications of SDI on Long-term Durability

An attempt is made here to project the results of the SDI testing toward the future conditions of the rocks. A hypothesis is proposed 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 shows two different types of the rate of degradation (weight loss) during the SDI testing.

The first type shows relatively linear decreases of the SDI as the number of test cycles increases (Figure 4(a)). This implies that each rock fragment in the drum has a relatively uniform texture (uniform degree of weathering, hardness, or strength) from the inner matrix to the outer surface. The lower the strength of the rock fragment, the higher the rate of degradation.

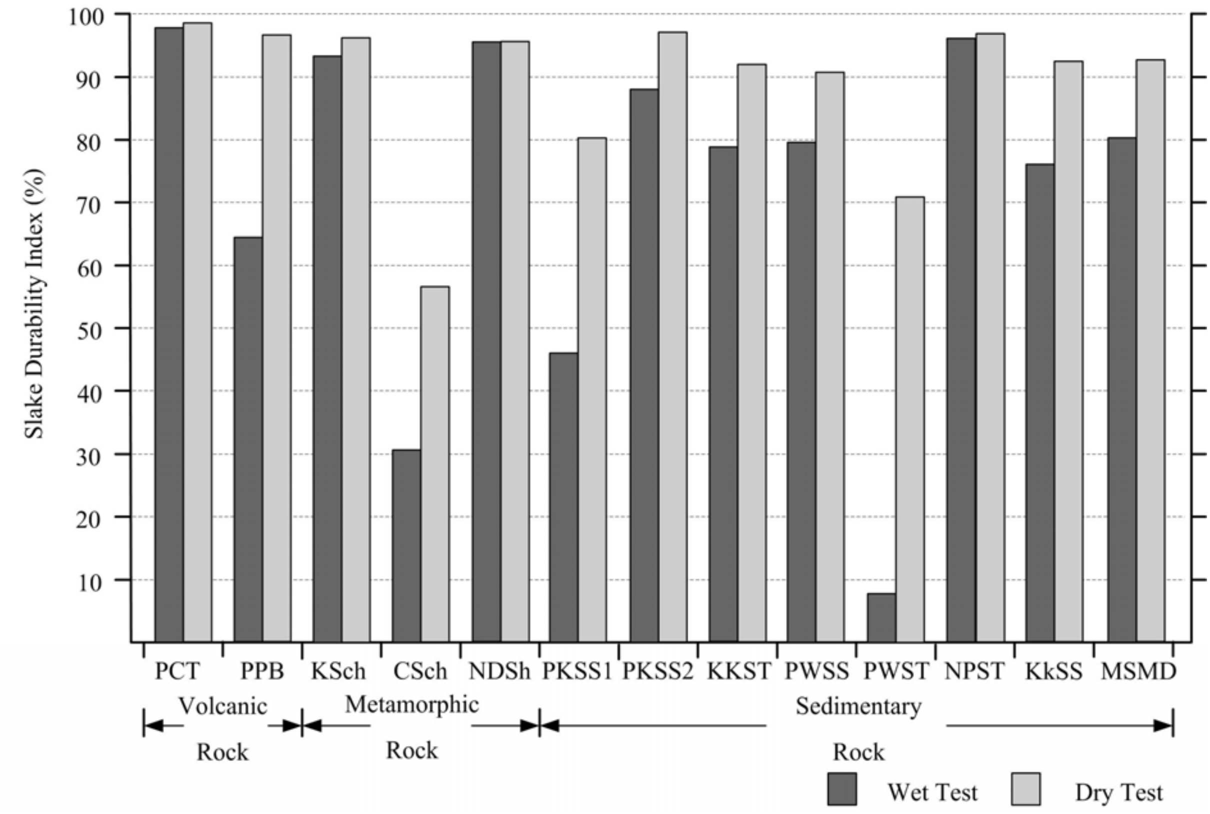

Figure 3 Comparison between SDI wet and dry test results at the sixth cycle

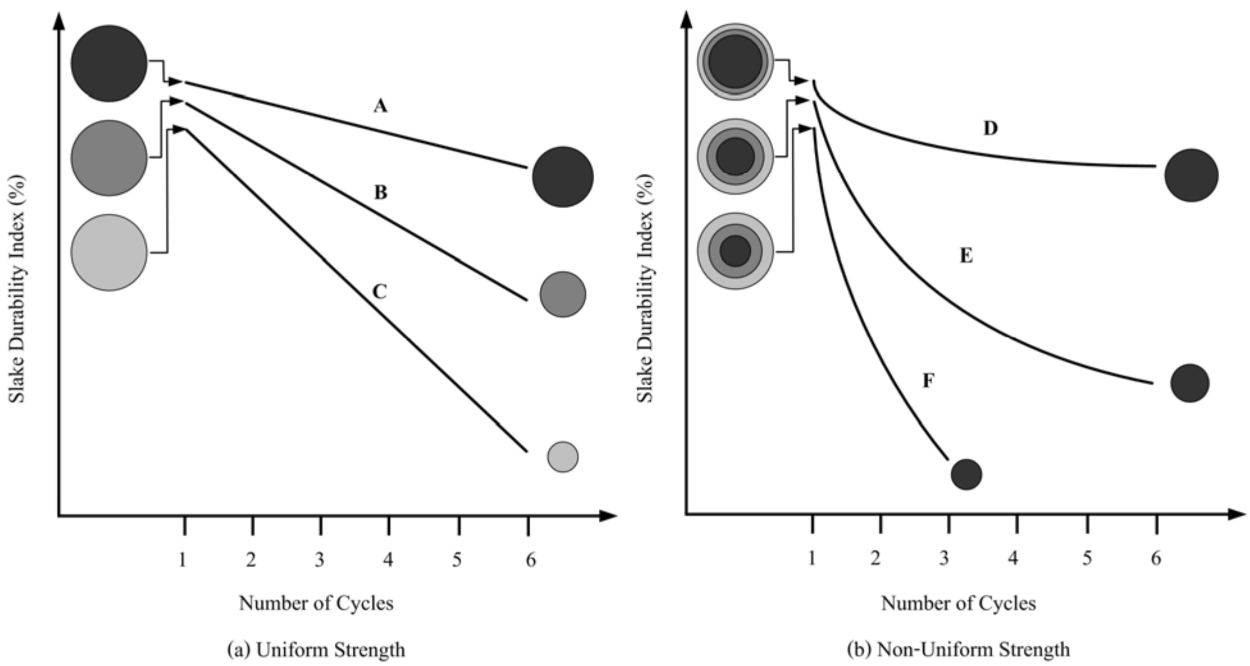

Figure 4 Proposed concept of rock degradation during SDI testing. Samples A, B and C (a) have uniform texture. Samples D, E and F (b) have weathered zone outside and fresher matrix inside

For the second type (Figure 4(b)) each rock fragment inside the drum has a 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, and the curves for samples D, E and F are concave upward. Here the decrease of the rock matrix strength from the outer surface to the inner part can be abrupt or grading, depending on the rock type and weathering characteristics. The more abrupt the change, the more concave is 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.

5. 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 larger number of SDI test cycles. When the rock fragments become stronger, the difference in the SDI values between the adjacent cycles (hereafter called ΔSDI) will also get smaller. In order to predict the rock durability in the future, the ΔSDI are calculated for the six cycles. Figure 5 plots the ΔSDI as a function of the reversed cycles, N^*. This is primarily to avoid confusing with the original forward cycles (N) defined earlier. This reversed plotting is mainly for a convenience in analyzing the test results. For example the ΔSDI that represents the difference between the SDI of the first cycle and the conditions as collected is plotted at $N^* = 6$. The difference between the SDI values between the fifth and sixth cycles is plotted for $N^* = 1$. For this new approach, while the ΔSDI increases with N^*, the rock becomes weaker. This is similar to the actual rock degradation due to the weathering process that has occurred in the in situ condition.

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. In Figure 5, the ΔSDI is projected to $N^* = 60$ cycles. Regression analyses on the 6 ΔSDI values indicate that an exponential equation can best describe the variation of ΔSDI with N^*. The implications of

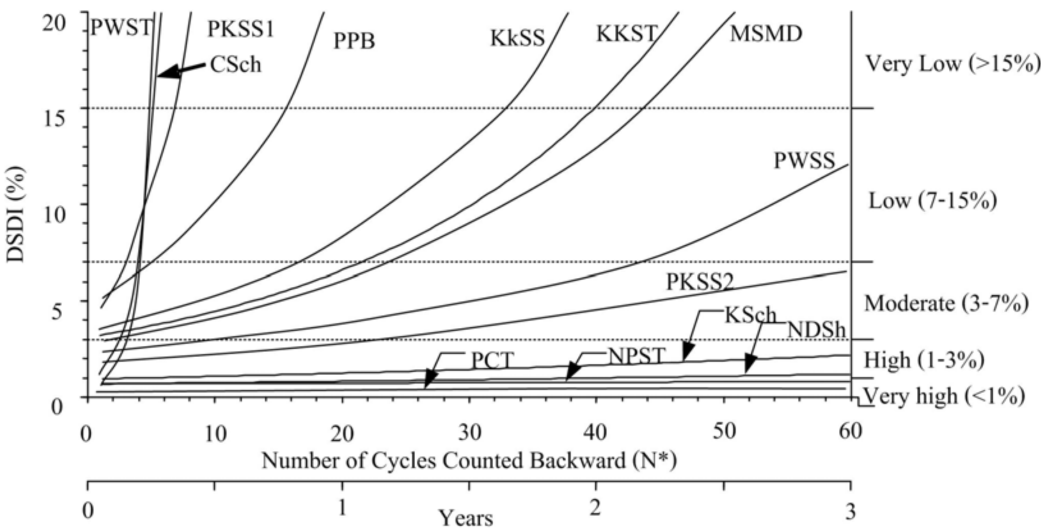

Figure 5 ΔSDI as a function of N^*. Rock conditions as collected are plotted at cycle no. 6

N^* and the actual time or duration for 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 later in this paper. Table 4 gives the empirical relationship, and summarises the constants obtained for each rock type.

6. Proposed Classification System for Rock Durability

A classification system is proposed for rock durability based on ΔSDI and its projected values to any N^*, as shown in Table 5. The ΔSDI–N^* curves obtained from thirteen rock types tested here are compared with the new classification system (Figure 5). For example, at $N^* = 60$ or below, Pichit crystal tuff, Nam Phong sandy-siltstone, Nam Duk slaty-shale, and Kanchanaburi green schist are classified as high to very high durability rocks. Pichit pumice breccia, Chonburi quartz mica schist, and Phra Wihan siltstone are classified as very low durability rocks, because their ΔSDI values rapidly increase within a few cycles of N^*. This agrees with the classification and conclusions drawn earlier from the results of the wet and dry SDI tests. It should be noted that the projection of ΔSDI – N^* curves relies on the number of cycles actually tested. A larger number of tested cycles may result in a higher reliability of the projected results.

Table 4 Empirical constants for exponential relationship between ΔSDI and N^*

Rock Types	ΔSDI = A•exp (B•N^*)		Correlation Coefficient
	A	B	
PCT	0.301	0.006	0.621
PPB	4.801	0.077	0.999
KSch	1.018	0.012	0.970
CSch	0.607	0.620	0.934
NDSh	0.728	0.008	0.959
PKSS1	4.465	0.189	0.930
PKSS2	1.828	0.021	0.999
KKST	3.055	0.040	0.999
PWSS	2.140	0.029	0.999
PWST	0.315	0.770	0.935
NPST	0.640	0.007	0.763
KKSS	3.402	0.047	0.999
MSMD	2.902	0.037	0.999

7. Simulation of rock degradation

An attempt to simulate the rock degradation was made in the laboratory. Fifteen rock cylindrical disks and 5 kg of rock fragments were prepared from 13 rock types. The specimens were placed in the oven at 110°C for 12 hrs and rapidly submerged in a tank of water at 25°C for 12 hrs. This rapid heating and cooling process was repeated 140 times (140 days). Weight loss, specific gravity, and water absorption of the fragment specimens was monitored at every 14 cycles (Figure 6). The procedure followed the standard practice [14]. At every 28 cycles, tilt testing was performed on three pairs of cylindrical disk specimens with smooth saw-cut surfaces to determine the change of the basic friction angle, if there was any.

The results show that Phra Wihan siltstone, Chonburi schist, and Pichit pumice breccia have a higher rate of weight loss than do other percentage of kaolinite in the rock matrix. This observation agrees with the results of the SDI testing reported earlier. Nam Duk slaty-shale also has a high rate of weight loss under this simulation because the high amount of mica content makes the rock disintegrate easily. Its fragments therefore become extremely brittle and weaker

Table 5 Proposed classification system for durability of intact rocks

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

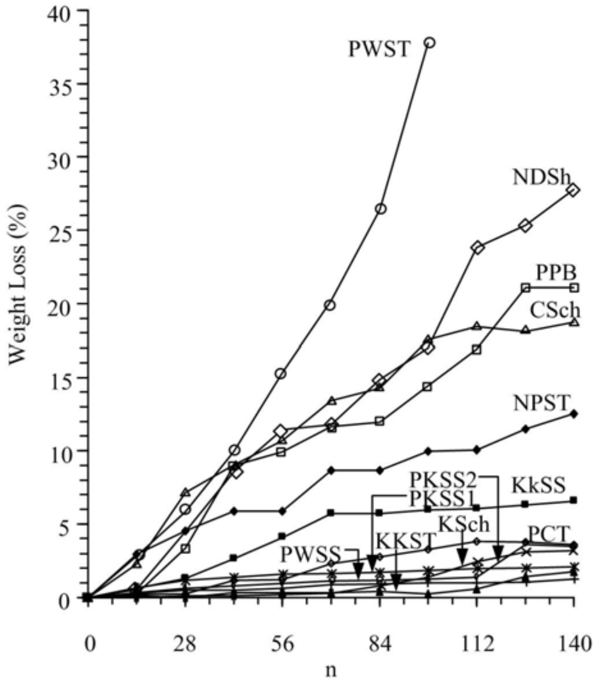

Figure 6 Weight loss of rock specimens moni-tored every 14 cycles of heating and cooling tests

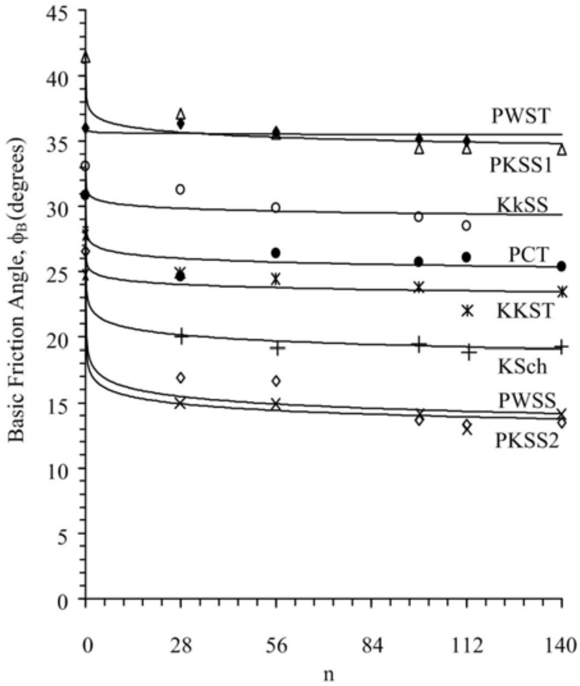

Figure 7 Basic friction angles of smooth (saw-cut) surface of rock specimens tested at various heating-cooling cycles (n)

when they are subjected to rapid changing of temperature. However, it is believed that this rock is not chemically sensitive to water, as evidenced by the results of the wet and dry SDI tests which showed that the SDI of the rock is relatively high. For all rock types the basic friction angles rapidly decrease during the first 28 cycles. After 28 cycles the decreasing rate becomes smaller (Figure 7). Variation of the friction angle with the number of cycles can be best represented by a power equation. Table 6 lists the empirical constants in the power equation for each rock type.

Table 6 Empirical constants form power equation relating ϕ_B and n

Rock Types	$\phi_B = C \cdot n^{-\lambda}$		Correlation Coefficient
	C	λ	
PCT	27.42	0.016	0.928
KSch	22.52	0.033	0.995
PKSS1	37.51	0.015	0.956
PKSS2	17.61	0.050	0.988
KKST	25.23	0.015	0.883
PWSS	18.55	0.055	0.953
PWST	35.73	0.002	0.469
KKSS	30.89	0.010	0.872

8. Relationship between Rock Strength and ΔSDI

A series of point load strength index tests was performed on all rock types. Two sets of specimens were used: the first set prepared from the samples as collected from the sites (n = 0), the second set from those after subjecting them to 140 cycles of heating-cooling simulation (n = 140 cycles). Prior to strength testing, both sets of specimens were also subjected to 6 cycles of SDI testing. The sample preparation and test procedure for the point load test followed the standard practice [15]. Table 7 compares the strength index values obtained from the two set of specimens along with the corresponding ΔSDI values (at $N^* = 6$). Strength results from specimens subjected to 140 heating-cooling cycles are lower

Table 7 Point load strength index results and their corresponding ΔSDI

Rock Types	Without heating-cooling cycle		140 cycles of heating-cooling	
	$I_{s(50)}$ (MPa)	ΔSDI (%)	$I_{s(50)}$	ΔSDI (%)
PCT	5.2	0.94	2.0	1.29
PPB	3.5	5.29	-	-
KSch	2.7	1.85	4.0	1.59
PKSS1	1.6	18.48	2.0	18.05
PKSS2	6.8	2.48	5.1	1.63
KKST	1.4	4.63	1.2	5.14
PWSS	2.3	16.33	2.4	3.92
PWST	1.0	6.60	-	-
KKSS	1.0	6.04	1.0	12.39
NPST	1.02	3.00	1.2	2.58
MSMD	1.0	48.82	-	-

than those not subjected to the heating-cooling cycles. This suggests that the heating-cooling simulation may have an impact on the rock strength. The point load strength results from both sets are plotted as a function of ΔSDI at $N^* = 6$, in Figure 8. Variation of the point load strength index with ΔSDI can be best represented by a power equation. This I_s–ΔSDI relation can be useful in correlating the physical properties with the mechanical properties of the rocks.

9. 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 those actually monitored in the field throughout the year. The heat energy absorbed by the rock can be calculated by using an equation [16],

$$Q = \sum_{i=1}^{n}\left(m \cdot C_p \cdot \Delta T_i \cdot \Delta t_i\right) \qquad (1)$$

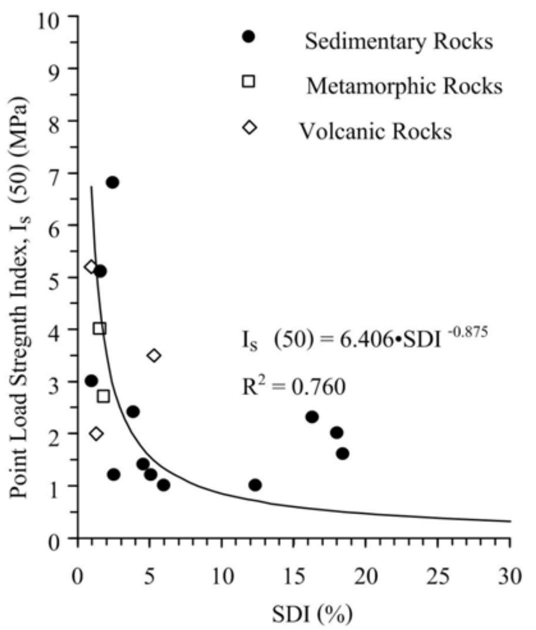

Figure 8 Point load strength index as a function of ΔSDI for all rock types

where Q is the absorbed energy of rock specimen (kJ), m is the mass of rock specimen (kg), C_p 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 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.

Using the above equation, the absorbed energy during heating simulation of most rocks is estimated as 4.320 MJ•hr (where m = 5 kg, C_p = 0.90 kJ/kg•K, ΔT = 80 K, t = 12 hrs).

For the in situ condition, the absorbed energy in one day is estimated as 0.245 MJ•hr (where m = 5 kg, C_p = 0.90 kJ/kg•K, ΔT is temperature change in each hour, t = 16 hrs.). Therefore, one simulation cycle of heating and cooling approximately equals to 18 days under in situ condition (4.320/0.245=17.84). 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. 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 $N^* \approx 18$ days. ΔSDI for each rock type shown in Figure 5 can therefore be calculated as a function of time.

10. Discussions and Conclusions

The factors affecting the degradation of the sedimentary rocks used in this research 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 thoe with lower density and higher amount of cementing materials. Kaolinite is highly sensitive to water which makes the rock disintegrate quickly. These observations agree reasonable well with those observed by Koncagul and Santi [3]. The effect of grain size cannot be studied because all the sedimentary rocks tested in this research are fine grained rocks.

For the metamorphic and volcanic rocks, kaolinite content seems to be the most important factor affecting the rate of degradation, particularly when subjected to water. The pore spaces in volcanic rock also enhance the weathering process by allowing more water to penetrate into the inner matrix. The metamorphic rocks with distinct foliation planes formed by the alignment of flaky minerals (such as mica) can notably disintegrate under cyclic changes of surrounding temperatures even under dry condition. The governing mechanism probably involves the differential thermal expansion of the rock forming minerals that have different thermal expansion coefficients. The cyclic changes of the temperature would induce repeated changes of shear stresses on the foliation planes and eventually cause separation between them. This effect is probably enhanced if the foliation planes that separate two different types of minerals are well defined and planar, and hence the shear stresses are induced along one common direction. This is supported by the progressive separation of the Nam Duk slaty-shale foliations observed in the laboratory which agrees with that observed on-site during the field investigation.

Reliability of the proposed ΔSDI–N^* relation may be increased for some rock type by performing a large number of SDI test cycles (more than 6 cycles as performed here). This would make the prediction more accurate. The N*–time relation probably varies among rock types, locations, depths, and climates. Obtaining a more accurate relation between N^* and time would require a field calibration which involves collecting and testing rock specimens under different periods of exposure within a span time of up to 10 or even 50 years. This approach becomes impractical. The approach used here is probably more practical.

The relationship between $I_{s(50)}$ and ΔSDI is developed by assuming that these values are independent of rock types. This assumption is made here because the amount of $I_{s(50)}$ data is limited (two for each rock type). It is believed that $I_{s(50)}$ - ΔSDI relation is unique for each rock type or at least for rocks with comparable origin, composition and texture. This is because the failure mechanisms for each rock cannot be directly related to the rock weathering under chemical and physical processes. Care should therefore be taken in applying this relation elsewhere as it may not be valid for other rocks with different physical and mineralogical characteristics from those tested here.

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. During each cycle of SDI test the rock fragments are also subjected to scrubbing action in the rotating drum. This process is more severe than what the rock would be subject to under in situ condition.

The uncertainties of the research results discussed above lead to the recommendations for further studies. 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. An attempt should be made to determine $I_{s(50)}$ – ΔSDI relation for individual rock type. This requires a large number of rock fragments for the point load testing, or rock cylinders for the uniaxial testing at several periods of degradation simulation. Such relation would provide a more accurate estimation for the long-term rock strength. A new or better approach may 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.

11. Acknowledgement

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