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Study on the physical disintegration characteristics of Subang claystone subjected to a modified slaking index test

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Abstract. Some instability problems were found on natural or engineered slopes mostly lying on Subang claystones. The instability problems included excessive erosion, slumps and rock falls. The field performance surveys of the problems suggested that the claystones physically weather rapidly so that the rock properties they exhibit during excavation often change to properties with a more characteristic of soil. Such a phenomenon is generally known as a slaking process. In order to gain better understanding about the slaking of Subang claystones, a series of experimental laboratory studies were carried out involving a modified slaking index test. Claystone samples used in this study were obtained from their exposures along the Northern West Java area of Indonesia. Petrographic analysis was correspondingly performed to identify mineral and texture/fabric, and in turn, to determine the inherent factors of the rocks which might affect the slaking process. The study results indicated that the claystones were characterized by high to very high slaking properties having a maximum slaking index (I_s) of 57.4% and a mean I_s of 43.8%. Major dispersion slaking on sample surfaces and high cracking in response to excessive swelling were recognized as main slaking modes within the claystones. All samples lose progressively less material through the five wet–dry cycles of a slaking index test, indicating a decelerated slaking rate. It was evident that the main inherent factors controlling the slaking process were expandable clay mineral smectite, non-clay mineral pyrite and soluble mineral calcite. Moreover, a quite important of inherent bonding material and stress release energy in the slaking characteristics of the claystones was revealed by a closure phase of an initial hairline crack during unloading.

Key words. claystone, index test, petrography, slaking, static slaking test, Subang formation.

1. Introduction

Claystones of the Subang Formation has widespread distribution at the northern areas of West Java, Indonesia. These claystones have specific characteristics, mainly found to exhibit slake-deterioration within a short period of time when exposed to

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the atmosphere and/or moistened, which then induce some significant problems in varied engineering activities. For instance, when the rock slope is being exposed due to an excavation, progressive near-surface slake-deterioration will be a major problem during its engineered lifetime. This problem can lead to high maintenance costs and may constitute a safety hazard; however, so far it received insufficient attention particularly at the design stage.

Until the last decade, the role of slake-deterioration on instability problems was an active area of study. An investigation conducted by Matsui and Shimada (1994) showed that instability problems were raised concerning the slaking of Ikeshima shale, resulting in the excessive roadway closures during mining operations. They further used such parameters to be included when considering the factors in the analysis of the support system design. Dick and Shakoor (1995) characterized slake-durability of mudrocks in various parts of the United States and Canada, and further suggested the classification for mudrock slope instability. Likewise, the study by Irsyam et al. (1999) found that the progression of rock slaking was responsible for numerous instabilities during the construction of Tulis hydroelectric power. They noted that due to excavation and progressive slaking, rocks lost their shear strength. Similarly, Park et al. (2000) have suggested the use of a proper number of slaking cycles of a slake-durability test for better representation on slope stability problems of weathered rocks in Korea. Previous researchers who also made similar observations include Cetin et al. (2000) and Wust and McLane (2000).

The susceptibility of rock to slake-deterioration is generally characterized by slaking tests. The basis of the test is to analyze their resistance to short-term weakening and disintegration or breakdown when subjected to a simulated rapid weathering process. There are in fact many different test procedures which are used to describe this parameter, and these tests can be categorized into two types; dynamic and static slaking tests. The fundamental procedure adopted in slaking tests is to immerse some rock samples in water while observing any disintegration that might occur. A widely known dynamic slaking test was proposed by Franklin and Chandra (1972), namely the slake durability test, which was already standardized and established by ISRM on the Suggested Method of Rock Characterization Monitoring and Testing (ISRM, 1981). However, there are some critics of the slake durability test because of its insensitiveness to those rocks that preferably broke off into small pieces with an average size coarser than the 2 mm. Subsequently, equidimensional roughly spherical sample shape with rounded corners that are needed in the rotation process caused further limitation to the test. This sample shape is frequently difficult to obtain, particularly for the samples having a peculiar behavior of easily splitting along the lamination or fissile present. Moreover, the test also employs a tumbling factor, which generally does not exist in the field. Meanwhile, it is surprising that there is no specified testing procedure for a static slaking test even though a number of experiments have been carried out, such as the ones performed by Morgenstern and Eigenbrod (1974), Wood and Deo (1975), Venter (1981), Ichinose and Matsui (1989), Santi (1998), Czerewko and Cripps (2001) and Sadisun et al (2002a). In general, the static slaking tests provide simple and reliable tests when the standard slake durability test is impermissible, particularly for medium to very weak rock materials (Sadisun et al., 2002a).

Santi and Koncagul (1996) mentioned some advantages in using the slaking index test which are as follows: (a) several wet–dry cycles may be carried out in the same sample in order to increase the rigorousness of the test, (b) the slaking index cycles represent the stresses material feels in nature due to wetting and drying, and (c) the numerical results enable a quantitative comparison between tested samples and remove subjectivity from the analysis. Furthermore, Santi (1998) suggested a modification focusing on the sieve washing proportion of the test. Sadisun et al. (2002b) slightly modified the test on the length of immersion time to be compatible with the immersion time of the slake-durability test (ISRM, 1981). Moreover, they also suggested the class value and slaking index classification obtained from the first cycle of the test. In addition, they improved the test results by including the observation index classification and introduced a slake-susceptibility index as a combination value of observation and slaking indices.

In order to gain better understanding about the slaking of the Subang claystones while taking the aforementioned slaking tests into consideration, a series of laboratory studies of static slaking tests was carried out with particular interest focusing on the characterization of slake-deterioration when subjected to a modified slaking index test. Petrographic analysis was concurrently performed to identify mineral and texture/fabric, and in turn, to determine the inherent factors of the rocks which might have an affect on the slaking process. Claystone samples used in this study were obtained from their exposures along the Northern West Java area of Indonesia (Figure 1).

2. Geological Overview Related to the Studied Area

The studied area falls within a unique condition of humid equatorial climatic regions which are often characterized with very high rainfall. The average annual rainfall reaches 3.140 mm, with a temperature variation of 18 °C to 31 °C and corresponding humidity values of 56–96%. Physiographically, this area is made up of Eocene–Oligocene non-marine clastics, overlying by Miocene and younger shallow shelf deposits of Northwestern Basinal Area (Darman and Sidi, 2000) with a gentle undulating and rolling topography. The Subang Formation as the main formation of interest described in this study is a part of the latest sedimentary sequence in these basinal areas (Figure 2). The stratigraphy and lithological characteristics of this formation have been extensively covered in numerous papers. Useful summaries were given by Martodjojo (1984) and Djuhaeni and Martodjojo (1989) that proposed the name of Subang for this formation into wide applications in geological mapping.

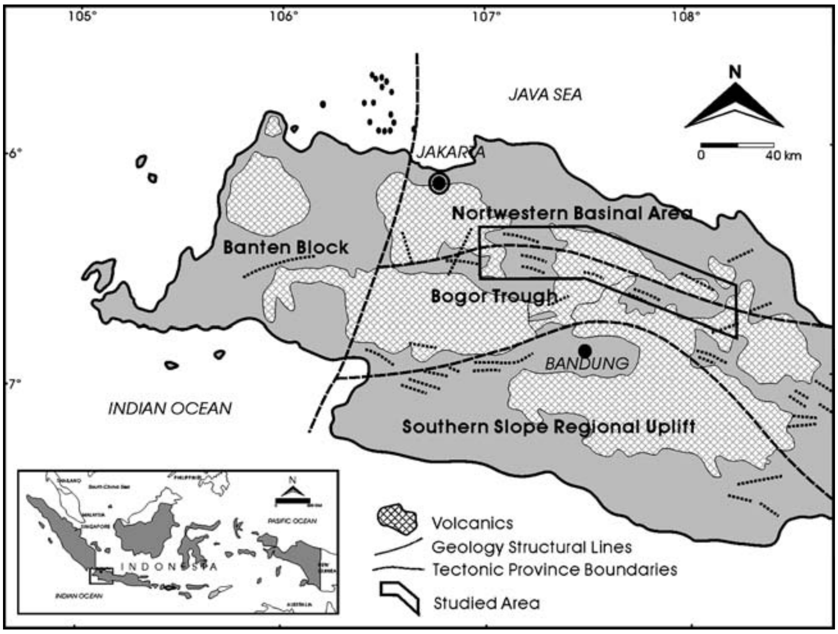

Figure 1. Reginal tectonic map of Banten-West Java, Indonesia (after Darman and Sidi, 2000).

In general, the Subang Formation is a Late Miocene–Pliocene marine deposits which are dominated by fine-grained lithologies and consists of mainly greenish grey to dark grey claystones, with some thin intercalations of fine-grained sandstones. The maximum-recorded thickness of the formation is about 2900 m which was measured at the Tomo area (Martodjojo, 1984).

Nine intact block samples of about $30 \times 30 \times 30$ cm^3 in size were selected on the basis of the aforementioned published papers and field surveys conducted by the authors. The field surveys suggested that the claystones physically weather rapidly so that the rock properties they exhibit during excavation often change to properties more characteristic of soil. They are relatively stiff and occasionally medium in hardness in an undisturbed state (large piece cannot be broken by hand), but they will progressively slake-deteriorate on their outcrops. These processes are taken up with some visible cracks which frequently occur together with volume changes (generally expansion) or noticeable heaving. Due to such characteristics, some instability problems were found whether on natural or engineered slopes and in fresh or weathered claystones. The problems included excessive erosion, slumps and rock falls (Figure 3). In order to obtain an intact block sample of the claystone, some of the outer slaked materials in the outcrops had to be dissected approximately more than 20–40 cm thick. Some samples were also collected from hand-excavated pits.

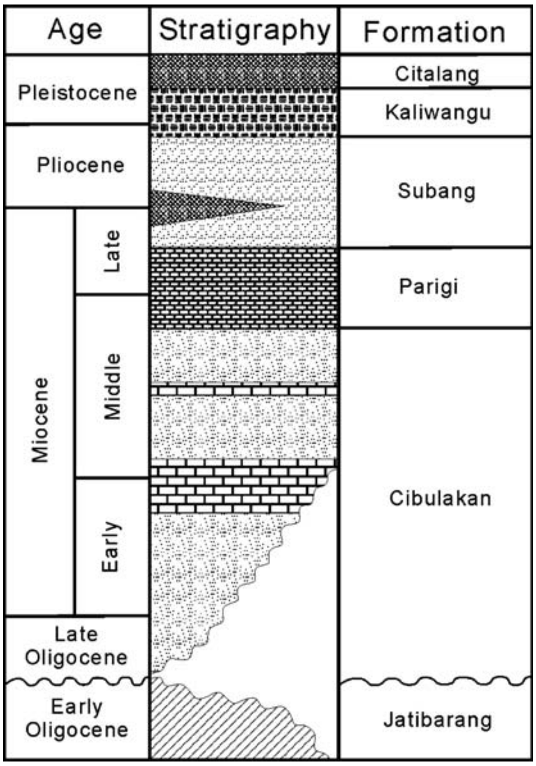

Figure 2. Regional stratigraphic column of northern shelf area of West Java (after Martodjojo, 1984).

3. Petrographic Properties of Subang Claystones

Based on visual petrographic analysis, all samples were easily characterized by fine- to very fine-grained textures, However, the claystones offered a visible marked difference in the style of cracking. The relatively weaker claystones usually showed many platy-cracking with the average thickness ranging from 2 to 4 cm of which such structural condition is usually known as flaggy (Figure 4). Meanwhile, the harder claystones exhibited concentric features whose spalling exposed a sub-spherical kernel.

For detailed petrographic analysis, an X-ray diffraction (XRD) method was used in order to determine the mineralogy of the rocks, while a scanning electron microscope (SEM) was used for the identification of minerals and the microfabric characteristics of the samples.

In order to determine mineral composition using the XRD method, a small portion of air-dried representative samples was pulverized using an agate paste and mortar. Powder fractions of rock were placed into the specimen holder and were compacted using filter paper with minimum effort, so as to induce as little particle

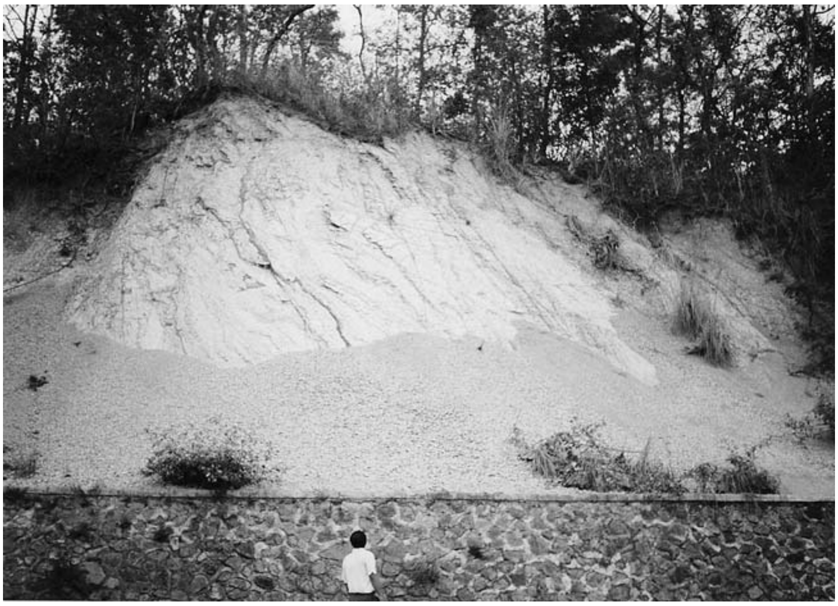

Figure 3. Rock falls in the roadside slope of Subang claystones resulting a thick mantle of regolith.

Figure 4. Field evidence for the typical development of platy cracking in an Outcrop of Subang claystone.

orientation as possible. The specimen was then inserted into the specimen chamber and scanned at a speed of 2° 2θ/min from the 2° to the 65° 2θ. Diffraction patterns were recorded on a strip-chard recorder and were determined by matching the diffraction patterns with the standard patterns prepared by the Joint Committee on Power Diffraction Standards (JCPDS, 1993). A detailed description of the method can be found elsewhere (Klug and Alexander, 1974; More and Reynolds, 1997). Some typical diffraction patterns including mineralogical analysis of Subang claystone are shown in Figure 5.

Quantitative analysis obtained from diffraction patterns was then performed by a reference intensity ratio (RIR) method based on measuring the intensity of one or more peaks for each mineral present and the added internal standard (Hillier, 2000). Table 1 shows a summary of the type and percentage of minerals present in the studied Subang claystones. The claystone tended to be almost uniform in mineralogical composition. It is quite obvious that most of the samples show an abundance of quartz, plagioclase, pyrite and clay minerals, i.e., kaolinite, illite, and smectite, with the other constituents of rutile, calcite and siderite. In this case, the first major mineral component is clay minerals, which have a considerable amount of predominantly smectite with a range of 13.1–47.5%, followed by a subordinate amount of kaolinite (12.5–25.0%) and a lesser amount of illite (0–10.3%). Quartz is a second major component of the claystone, ranging from 11.5% to 36.4%. Meanwhile, the amounts of other minerals were varied and some of them were only found as possible tracing minerals, such as rutile and chlorite.

A SEM was used for the examination of the microfabric characteristics of the samples. The fundamental basis of the equipment is the irradiation of specimens with a beam of accelerated electrons under conditions of high volume, which produces a range of particles. The SEM images are captured by a common scanning technique as described in detail by Goldstein et al. (1984). Figure 6 shows the ideal scanning electron micrograph of wavy sheet structures of smectite in the Subang claystone among little fibrous structures of illite. An examination of intact samples under SEM also revealed that the samples were characterized by a thin parallel arrangement, which might indicate a dispersed structure (face-to-face oriented structure) resulting during consolidation. This structure usually implies that the claystones are low in permeability and relatively stiff. However, there were also some flocculated structures (edge-to-face oriented particles) identified within the claystones behaving more sensitively to disturbance than the dispersed structures.

4. Basic Engineering Properties of Subang Claystone

The natural moisture content of the Subang claystones was high, ranging from 21.61% to 52.54% and 36.45% on average. Whereas, the bulk density of the claystones averaged 1.91 g/cm^3 with a range of 1.64–2.25 g/cm^3 and the average of effective porosity was 6.74%, ranging from 3.69% to 9.66%. In a previous study, Sadisun et al. (2001) found that the claystones, according to Broch and Franklin (1972), were low to

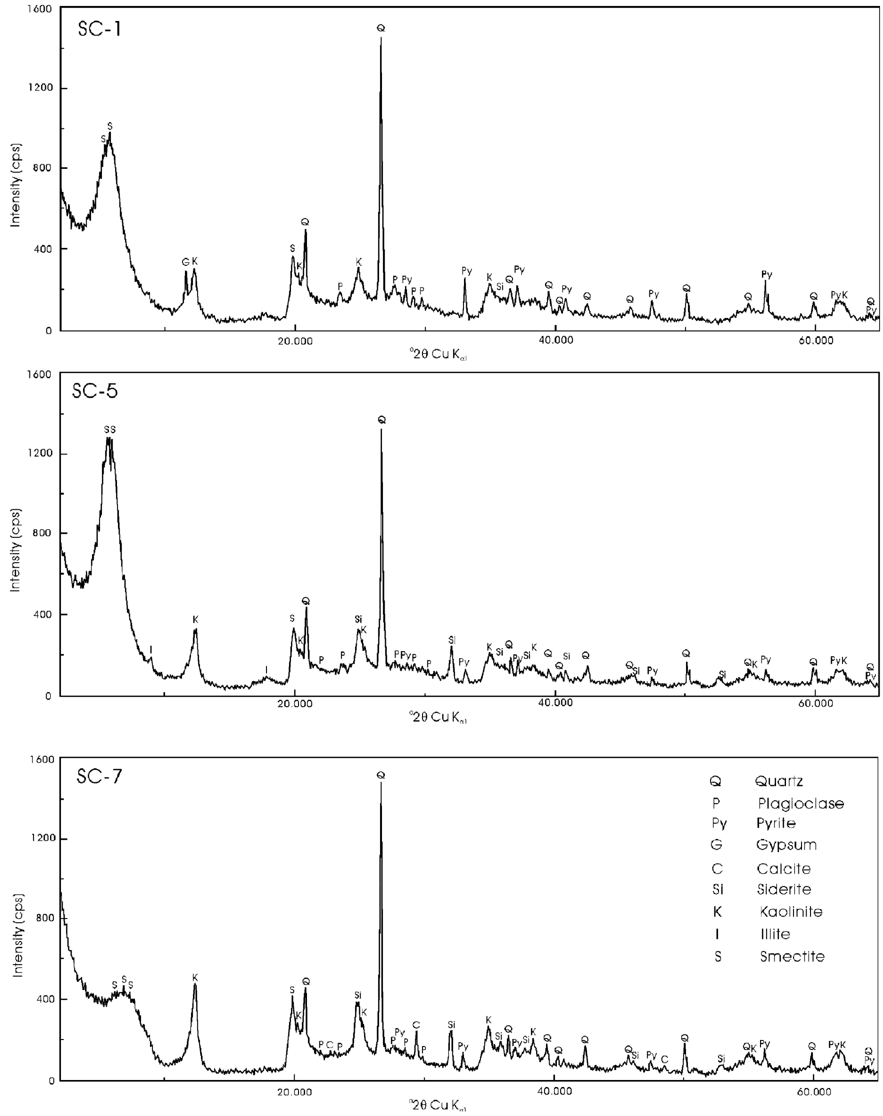

Figure 5. Some typical X-ray diffraction patterns of Subang claystones including mineralogical analysis (SC-1, SC-5, SC-7).

medium in strength when examined by a point load test at *in situ* moisture content. The different strength claystones tended to correspond with the relative stiffness marked during field observation. For all samples tested in this study, the minimum point load strength recorded was 0.17 MPa and the maximum was 0.56 MPa, with a mean value of 0.21 MPa.

Table 1. Mineralogy of Subang claystone

Mineral	SC-l	SC-2	SC-3	SC-4	SC-5	SC-6	SC-7	SC-8	SC-9
Quartz	25.0	17.4	14.6	18.7	11.7	11.8	14.2	36.4	20.2
Plagioclase	13.8	8.8	8.9	15.4	5.6	5.2	6.2	13.3	14.2
Pyrite	5.2	13.6	12.7	9.4	7.6	8.8	7.7		
Rutile						Tr*			
Gypsum	4.0		6.9	8.9		8.5			
Calcite		10.7				Tr*	10.7	Tr*	10.1
Siderite		12.3		Tr*	9.3	8.5	11.0	Tr*	8.4
Kaolinite	12.5	17.4	20.5	16.2	10.5	12.8	17.4	25.0	18.4
Illite		6.7	6.6	Tr*	7.8	5.4	Tr*	8.7	10.3
Chlorite		Tr*						Tr*	Tr*
Smectite	39.4	13.1	29.8	31.3	47.5	39.0	32.9	16.6	18.4

*Tr = Poorly traced minerals that can not be appropriately quantified.

The greatest variation found in the engineering properties of the claystones can be attributed to the effects of weathering (Sadisun and Matsui, 1999). Weathering eventually returns claystones to a normal consolidated condition by breaking the bounds between particles. For instance, there was a difference of 32.65% in the value of shear strength and 47.45% in compression strength between fresh and weathered samples of the claystones tested in the direct shear test and point load test, respectively. Therefore, as a main mode of the physical weathering process, slaking is one of the most important engineering properties of the claystones when various engineering activities involve their exposure to weathering.

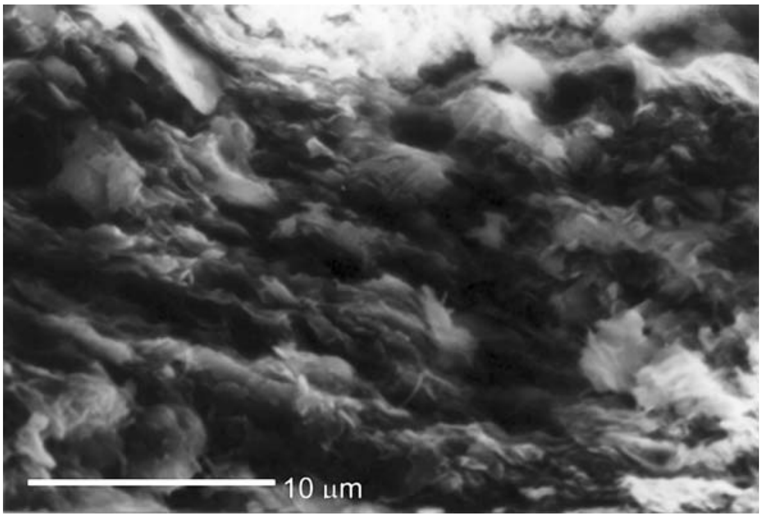

Figure 6. An ideal scanning electron micrograph of wavy sheet structures of smectite among little fibrous structures of illite.

5. Laboratory Testing of Slaking

A series of static slaking tests have been carried out. At a fundamental level to understand the detailed mechanism of slaking behavior, the development of incipient discontinuities into open cracking was investigated by slaking exposure, slaking immersion and dry–wet cyclic slaking tests involving qualitative observations of the slaking process. All samples were then described in terms of crack development and any disintegration that might occur as listed in Table 2. Moreover, slaking class was allocated according to Sadisun et al. (2002b). In order to gain better visual characterization, a loupe having a magnification of 10× and 30× was used. Meanwhile, for quantifying the amount of slaking and as the main procedure of the static slaking test of this study, a slaking index test was performed following Santi's (1998) modifications and Sadisun et al.'s (2002b) recommendations.

In general, there is no complicated specimen preparation needed in the laboratory slaking tests. The specimens for the slaking exposure, slaking immersion, and dry–wet cyclic slaking tests have the same dimensions which are cube specimens with sides of 4–6 cm. For other slaking tests, it is sufficient to use irregular forms of rock lumps. Natural conditions of specimens are maintained in the slaking exposure and slaking immersion tests. However, for dry–wet cyclic slaking and slaking index tests, the samples are dried in a thermostatically controlled drying oven to a constant weight.

In the slaking exposure and slaking immersion tests, samples are left under a free air condition and water immersion, respectively, at room temperature. Whereas, the dry–wet cyclic slaking observation test consists of heating the specimens in an oven at 105°C for 24 h and then immersion in water for 48 h. This represents one cycle and specimens are subjected to the same treatment during a successive cycle.

The procedure of a slaking index test is quite similar to the dry–wet cyclic slaking test. In this test, the test samples consist of six pieces of rock lumps which have a mass between 100 and 150 g. Each piece of the test sample is then placed in a separate beaker and oven-dried to a constant mass at 105°C. This usually takes about 4–6 h.

Table 2. Criteria for visually classifying Subang claystones to slaking

Class	Criteria
0	No visible change or change can be allowable as only very minor hairline cracking
1	Severe hairline cracking without spalling, and/or mud-sand particles starting to breakaway from the rock surface
2	Crack opening with minor spalling and/or little suspended mud-sand particles
3	Further process of crack opening with major spalling and/or suspended mud-sand particles
4	Complete disintegration to a mound of chips and/or remarkable portion of suspended mud-sand particles

Note: Classes correspondingly denote the degree of disintegration.

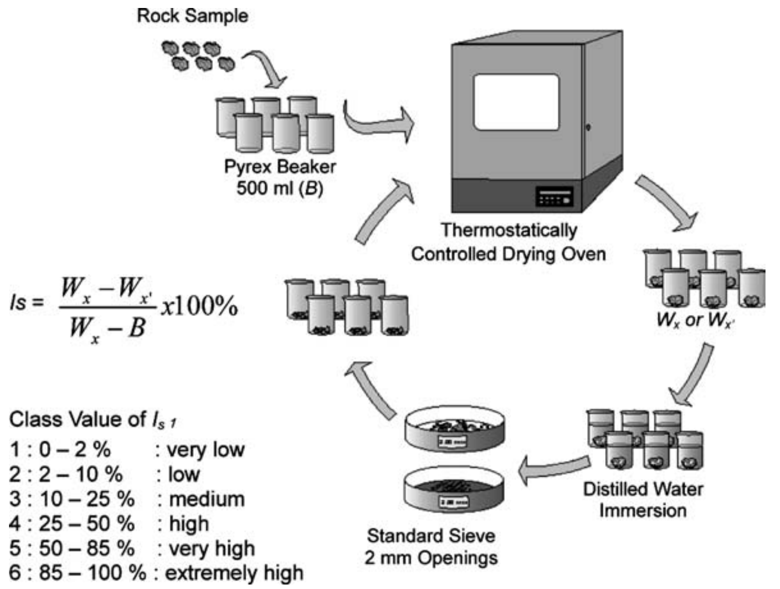

Figure 7. A schematic diagram of modified slaking index test and its suggested classification.

After cooling at room temperature, the water then is poured into the beakers so that the samples are covered by at least 10 mm of water. After 12–16 h of immersion, the samples in each beaker are washed with tap water/distilled water on a 2 mm standard sieve (# 10 sieve). The material retained on the sieve is then put back into the beaker, decanted and oven-dried to a constant mass. The percentage of loosen sample to initial oven dried mass is calculated and recorded as a slaking index value (I_s) for that cycle, or it can be defined as an equation:

$$I_s = \frac{W_x - W_{x'}}{W_x - B} \times 100\%$$

where W_x = total mass of the 6 beakers and oven dried material; $W_{x'}$ = total mass of the 6 beakers and oven dried material retained on the 2.00 mm sieve; B = total mass of the 6 beakers, Figure 7 illustrates, in brief, the procedure of the slaking index test.

In order to verify the petrographic effects on the slaking process, some claystones were also submitted to the slaking index test in an aqueous solution, such as hydrochloric for acid and calcium carbonate for alkali, with varied concentrations.

6. Results and Discussion

6.1. FUNDAMENTAL SLAKING PHENOMENA IDENTIFIED IN SUBANG CLAYSTONES

The deterioration process of the claystones when subjected to the slaking exposure test offered the characteristic that most specimens initially deteriorated after 4–24 h exposure, which revealed some minor hairline cracks commonly starting on the edges of the specimens. Stronger specimens usually possessed a medium strength and tended to survive until more than 24 h after exposure. An ideal crack progression due to slaking on Subang claystones under an outdoor exposure condition was visually characterized as shown in Figure 8.

Under water saturation, most specimens were disaggregated or the particles dispersed quickly. In this test, the specimens showed several hairline cracks within less than 3 min, while the stronger ones tended to sustain hairline cracks after 5 min. The full disaggregation/disintegration occurred during the 1–4 month period. The principal difference between low and medium strength claystones in the slaking process with emphasis on the characteristic of physical disintegration was when the low strength claystone was immersed in water, the cloudiness could easily develop and slowly precipitate around the base of the specimen. However, in medium strength claystone, the specimen showed a sign of some collapse (mainly just at the edges) into angular pieces with only a slight cloudiness. Pieces of material remaining, arising from the disaggregation process, were then gently broken down by conducting some agitation.

A similar result was also shown when the specimen was assessed by being subjected to cycles of wetting and drying, in which most specimens fully disintegrated after two cycles, with the exception of two medium strength claystone specimens tending to survive in the third cycle. Severe hairline cracking invariably developed immediately during oven drying in the first cycle of every specimen tested. Moreover, some of them also showed open cracking and even possessed a minor spalling. Again, the medium strength claystone was more resistant than the low one. All results of the dry–wet cyclic slaking observation test are listed in Table 3.

Regarding the four common modes of slaking suggested by Moriwaki and Michell (1977), we could visually identify that the Subang claystones were subjected to each slaking mode. Figure 9 shows the suggested typical sketches of all slaking modes obtained form the cube claystone specimens consisting of dispersion slaking, surface slaking, swelling slaking and body slaking. It was mentioned before that the cloudiness was easily developed around the low strength claystones. This means that these claystones tended to dominate dispersion slaking during immersion, although they also suffered body slaking. In this case, the body slaking mode of the claystones could be more obviously recognized when they were subjected to the slaking exposure test (see Figure 8) Meanwhile, the slaking mode of medium strength claystones was mainly surface slaking, whether upon immersion or exposure. For the swelling

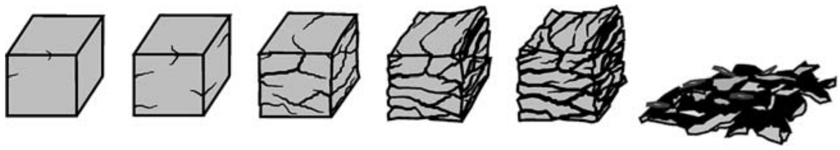

Figure 8. An ideal crack progression due to slaking on Subang claystones under an outdoor exposure condition.

Table 3. Summary results of some fundamental static slaking tests

Sample #	Time to initial slake (h:m:s)		Dry–wet cycles					Slake-susceptibility index
	Exposure	Immersion	Dl	W2	D2	W2	D3	
SC-1	11:46:00	0:03:32	1	3	4			6
SC-2	26:35:00	0:05:17	1	2	3	3	4	6
SC-3	24:12:00	0:04:02	1	2	3	4		6
SC-4	9:44:00	0:04:48	1	3	3	4		7
SC-5	4:30:00	0:03:08	2	3	4			8
SC-6	13:20:00	0:03:58	2	3	4			8
SC-7	19:58:00	0:04:31	1	3	3	4		7
SC-8	28:06:00	0:05:28	1	2	3	3	4	6
SC-9	25:14:00	0:04:36	1	3	3	4		6

slaking mode, it was quite difficult to identify the direct effects of this mode individually because the swelling process will usually also generate cracking in the specimen. However, the swelling phenomenon could be indirectly inferred due to the fact that the Subang claystones contain plenty of widely known expandable clay mineral smectite. Furthermore, during cracking progression of body slaking or surface slaking, air bubbles were released which usually result in slaking acceleration.

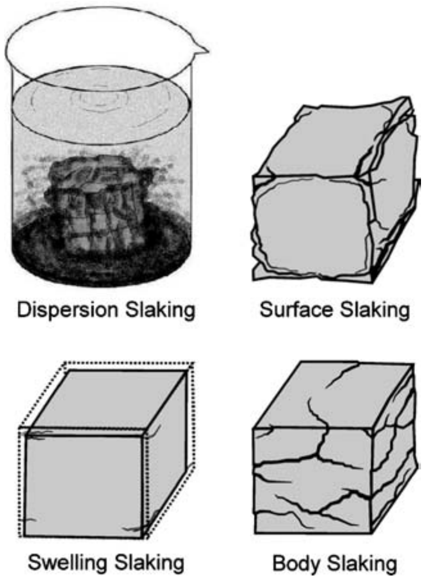

Figure 9. Suggested typical sketches of all slaking modes obtained form the cube specimens of Subang Claystones.

6.2. SLAKING INDEX CHARACTERISTICS OF SUBANG CLAYSTONES

Slaking indices obtained from a slaking index test are shown in Figure 10. The slaking indices tend to increase with the increasing number of cycles. On the basis of slaking index classification suggested by Sadisun et al. (2002b), the claystones possessed a high to very high slaking characteristics having a maximum slaking index (I_s) of 57.4% and a mean I_s of 43.8%. It can be clearly identified in Figure 10 that there are flattened lines, which indicated that all samples lose progressively less material through the five wet–dry cycles of the slaking index test. In other words, the slaking indices rapidly increase on the first cycle and the second cycle, followed by slight increases in the fifth cycle; therefore, the fifth cycle value is less than five times the first cycle value. Such characteristics were suggested as decelerated slaking characteristics because there is a decelerating rate of the slaking process. Furthermore, concerning the last cycle of the test, it can be recognized that the weight values of the specimen sustain almost complete slaking failure, which may represent the long term response of the claystones to physical slake-disintegration.

During the slaking index test, visual slaking characterization was also conducted in order to verify the slaking mode resulted from slaking exposure, slaking immersion and dry–wet cyclic slaking tests. There was an agreement that for high slaking claystones, the dominant slaking mode was surface slaking. Meanwhile, the very high slaking claystones were dispersion slaking and severe cracking resulting from whether body or swelling slaking. These phenomena appeared to be also corresponding with the relative stiffness of the claystone, as such phenomena were also found during field surveys.

As visual slaking characterization was also carried out during the slaking index test, all samples were also described using similar criteria to those applied for visual

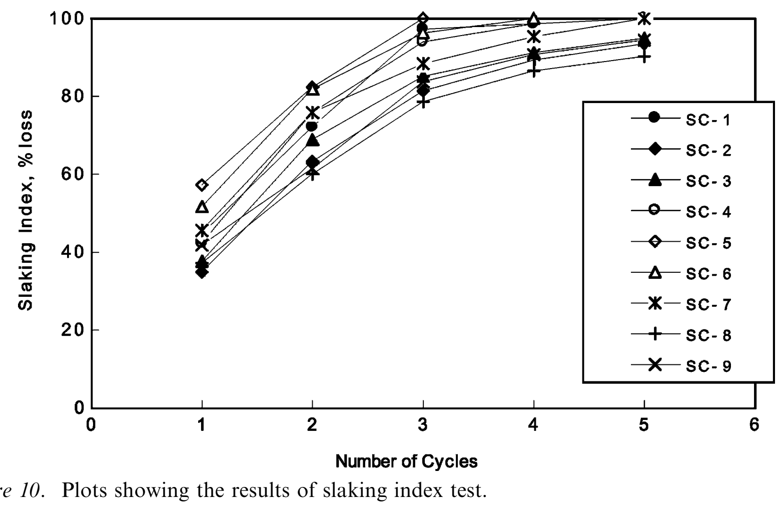

Figure 10. Plots showing the results of slaking index test.

index tests just before sieving of the first cycle. Therefore, slake-susceptibility indices of the claystones, resulting from further evaluation of slaking index test, were ranging from 6 to 8, which meant high to very high acceleration in weakening and physical disintegration after their exposure and moisture level. All slake-susceptibility indices are also listed in Table 3.

The differences in whether the slaking index or slake-susceptibility index could be explained in terms of inherent petrographic characteristics to each claystone will be thoroughly discussed in the following section.

6.3. PETROGRAPHIC EFFECTS ON ROCK SLAKING

The two major petrographic aspects of the rock which might affect the slaking process are mineral and texture/fabric. By definition, claystones are usually determined as fine-grained clastic sedimentary rocks made up of more than 2/3 percent clay-sized ($<1/256$ mm) particles, of which mainly consist of clay minerals, mica, and quartz grains. In general, there are three textural components to most clastic sedimentary rocks including: (a) fragment/clast (gravel, sand, silt), (b) matrix (fine-grained material surrounding fragment), and (c) cement (silica, calcite, or iron oxide-adhesive substances that hold the rocks together).

Based on the petrographic characteristics, it is obvious that the slake-disintegrations in the claystones are due to specific meniralogical/textural relationship. It is already well-known that the rocks containing smectite and pyrite minerals may disintegrate when they are exposed to the air and water. As both of these minerals were found in the claystones, it was suggested that they might be possible factors influencing the slaking process. Furthermore, soluble calcareous minerals were found in the claystone, which might also affect the slaking process, although this could have taken place for a long period of time. Regarding textural characteristics of the claystones, resulting from a very long diagenetic process through their geological history, they might contain a certain degree of release energy which is also probably significant in the controlling of the rock to potential slake.

In the following section, the aforementioned petrographic factors that were believed to have affected the slake-disintegration of the claystones will be discussed.

6.3.1. *Swelling of Expandable Minerals*

Smectite is widely known as the most expandable clay mineral. This mineral was recognized as whether individual-layered or interstratified-layered minerals and mostly as a part of matrix. In order to recognize the influence of smectite on slake-disintegration, a correlation analysis was carried out between the percentages of expandable mineral and slaking indices. From the slaking index-smectite content relationship curves shown in Figure 11, it can be identified that the slaking indices increase with the increase of the smectite content, which shows a quite positive linear

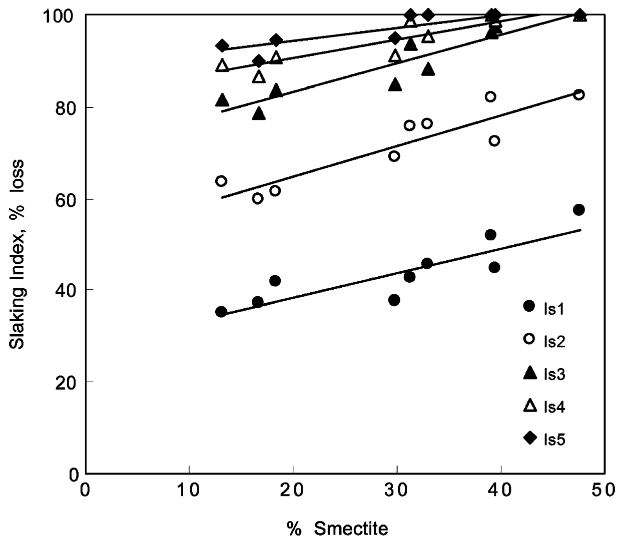

Figure 11. Slaking index-smectite content relationship curves.

relationship. The relationship has just not only able to be identified on the first cycle (I_s) of the test but it can be also identified on the other following four cycles (I_{s2}, I_{s3}, I_{s4} and I_{s5}).

The diffuse double-layer theory is usually applied to explain the deformation between two parallel smectite layers (see Van Olphen, 1991). Osmotic pressures develop between clay particles as water is drawn into the zone of a double layer between clay surfaces where there is a greater concentration of ion compared to the external solution. Depending on the strength of the electrostatic attractive forces between the exchangeable cations and the clay, the double layer may expand. This expansion allows the water content to increase, and in many cases, allows the rock to slake.

In addition to smectite, another mineral that can be identified as an expandable mineral is a non-clay mineral pyrite, which were mostly identified as framboidal fragments and small stratified cubes under SEM. Pyrite is stable only under a strongly reduced oxygen condition. Generally, when the pyrite is exposed, it will oxidize to ferrous sulphate and free sulfuric acid, which can be described by the reaction:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4 \quad (1)$$

$$FeSO_4 + 2H_2O \rightarrow Fe(OH)_2 + H_2SO_4 \quad (2)$$

If any calcium carbonate is present, as also found in some samples of Subang claystone, free sulfuric acid resulting from the oxidation of pyrite may alter into sulfate (gypsum), promoting a slow increase in volume, and hence, in rock cracking, The reaction process can be written as:

$$H_2SO_4 + CaCO_3 + 2H_2O \rightarrow CaSO_4 \cdot 2H_2O + H_2CO_3 \qquad (3)$$

In this study, a further test was carried out to understand the slaking behavior of pyrite bearing rock in distilled water and $CaCO_3$ solution in a different concentration (Figure 12), It can be recognized that the slaking indices in $CaCO_3$ aqueous solutions are always higher than that in distilled water, Moreover, the observed slaking indices increase as the $CaCO_3$ concentration increased.

6.3.2. *Precipitated of Soluble Minerals*

Some claystones contained soluble minerals of calcite, mainly occurred as very small crystals of pore-filling materials. To verify the importance of these minerals in slaking behavior, other samples of the claystone were submitted to the slake index

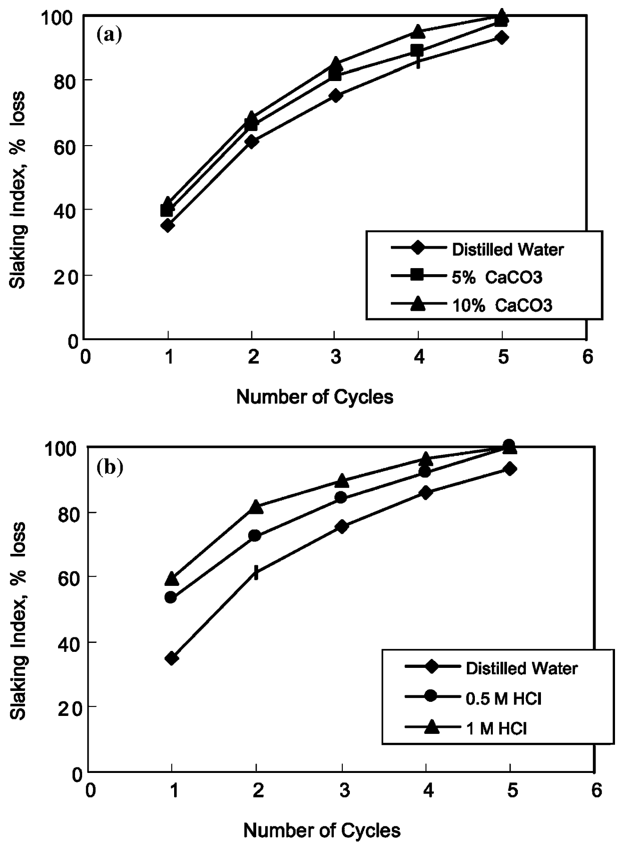

Figure 12. Results of slaking index test in water and (a) $CaCO_3$ solutions (b) HCl solutions.

test in the HCl solutions of different concentrations (see Figure 12). The results are quite similar to the use of the $CaCO_3$ solution where slaking indices increase with an increasing concentration of HCl solution. This demonstrates the grave importance of calcite soluble minerals in the slaking behavior of argillaceous rocks, particularly in the acid condition.

6.3.3. *Release Strain Energy*

In spite of the two specimens being equal in percentages of smectite and pyrite minerals, they occasionally exhibit a difference in the values of slaking indices. This may indicate that the claystones structure/fabric contained a certain degree of strain energy (dissipation energy), which also affects the slaking process. In this case, the extension or release of the stratified structural planes seemed as the dominant factor controlling the slake-disintegration revealed by a closure phase of cracking or fissuring that developed when they were initially exposed to the atmosphere. These processes were occasionally hard to detect by the naked eye without using at least a 10× magnification loupe for hairline cracks that were mostly developed. The cracks would further result in increases of permeability and exposed rock surface area where in any expandable minerals allowed reaction with water. The increase of permeability by developed cracks was also a main factor triggering capillary forces. Taking all this into consideration, it is not unreasonable to understand that the inherent energy release significantly contributed to the slaking process.

7. Conclusions

In order to gain better understanding about the physical disintegration characteristics of Subang claystones, a series of laboratory studies were carried out involving a modified slaking index test. Several conclusions may be drawn as follows:

- Time needed to initiate slake-disintegration was identified. Under a dry exposure condition, most claystones were initially slaked after 4–24 h, but under a saturated condition they slaked quickly within less than 5 min, Severe hairline cracking invariably developed immediately due to oven drying.
- The common mode of slaking could be clearly recognized by static slaking tests, in which major dispersion and swelling slaking were recognized as the main slaking modes within the claystones.
- The slaking index test indicated that that the claystones were characterized by high to very high slaking properties having a maximum slaking index (I_s) of 57.4% and a mean I_s of only 43.8%. They also possessed decelerated slaking characteristic and sustained almost complete slaking failure through the five wet–dry cycles of the test. Further analysis using a combined value of observation and slaking indices suggested that the slake-susceptibility indices of the

claystones were ranging from 6 to 8, which mean that the claystones could be easily weakened and physically disintegrated in a short period of time after their exposure and changes in moisture level.

- It was evident from petrographic analysis that the main inherent factors controlling in the slaking process of the claystones were expandable clay mineral smectites and non-clay mineral pyrites. The occurrence of soluble mineral calcites also took a significant role in the slaking process, which usually occurred as bonding materials. Due to their exposure and unloading, a quite importance of inherent stress release energy was revealed by hairline cracking as an initial slaking process.

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