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SLAKE DURABILITY OF THE COMPACTED-SILTSTONE FRAGMENT WITH CEMENT STABILIZATION

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ABSTRACT: Cement stabilization is a practical improvement method of the soil bearing capacity of problematic soils. Soil bearing capacity is attributed to its strength and durability. The decrease in durability can be caused by weathering. On this account, to improve the long-term behavior of soil experiencing weathering process, it is necessary to apply cement stabilization to ensure the quality of road performance. This paper presents the results of a laboratory investigation on slaking index and the physical change of cement-stabilized soil. A new sample preparation method of stabilized soil is presented in this study for the slake-durability test. The cement content was varied from 2 to 10 percent of the dry soil. The test results show that the unstabilized compacted-siltstone was ruined on the first test cycle. In general, the degree of slaking (Is) increases with the slaking cycle but decreases with the cement content. Whereas, the slaking durability index ($I_{d(2)}$) increases as cement content increases. A large quantity of cement was required to obtain a successful stabilization. This study recommends that 7% of cement is suitable for soil modification, while 10% of cement satisfies the requirement for stabilization.

Keywords: Slake-Durability Index, Degree of Slaking, Slaking Cycle, Compacted-Siltstone, Cement Stabilization

1 INTRODUCTION

Some sections of toll road in Indonesia were constructed over soft soil and soft mudrock type. The soils are typically a problematic soil, which caused the construction failure, e.g. at Semarang-Bawen toll road section [1], and Cipularang toll road section [2]. Those soils were susceptible to weathering and strength degradation [3]-[7]. Hartono et al. [8] proposed cement stabilization to improve the strength of the soft mudrock in Semarang-Bawen toll road section. Cement stabilization is commonly and practically used to improve the engineering properties of a problematic soil [9]-[13]. Soil bearing capacity is attributed to strength and durability. The decrease in durability can be caused by weathering. Thus, to improve the long-term behavior of soil experiencing weathering process, it is necessary to apply cement stabilization to ensure the quality of road performance.

Some studies have developed a method for measuring the durability of rock type fragments [14]-[18]. Slaking tests is a common method to determine the deterioration level by measuring the resistance due to rapid weathering. Although many methods were applied in slaking test, there are two major groups of tests: (1) dynamic, and (2) static slaking test. The standard test of the dynamic slaking test has been secured in ASTM D4644 [19]. The standard is adapted to examine the durability of the soft-rock weathering due to wetting and drying cycles. In the slaking test, weathering is a complex process involving a simultaneous rotation, sliding, and crushing of the specimen against water immersion [20]. Many factors affect the slake durability tests such as porosity and permeability, testing fluids, the rock stability against swelling and decomposition, the profile of sample pieces, size and weight, properties of testing equipment, storing conditions, and the frequency of wetting-drying cycles [14], [21].

The standard test for slakes durability measures the slake durability index and weathering type after two times of wetting-drying cycles. Some studies performed the weathering process up to five to 12 cycles. The result of the slake durability test is stated in term of slake durability index ($I_{d(2)}$) and weathering type at the end of the cycle. The specimens for the slake durability test is commonly intact fragments or pieces of rock. ASTM D4644 defines the weathering into three types: (1) retained specimen remaining virtually unchanged (Type I), (2) large and small fragments of the retained specimen (Type II), and (3) retained specimen of exclusively small fragments (Type III). Cano and Tomás [17] added the ASTM D4644 criteria by roundness, fragment size, and variation in the number of fragments between two sequent cycles.

Slake durability test has been intensively investigated to evaluate the stability of mudrock

[22]-[26]. However, there were only a few studies of the slaking test conducted on remolded and stabilized samples. The specimen's size of the remolded samples was not standardized. Ghosh and Subbarao [27] used a cylindrical specimen of 38 mm in diameter and 76 mm in height. However, there was no standard test on stabilized soil that corresponded to cycle time, size, and shape of the specimen. Some studies used the cylindrical shape of 38 mm in diameter and 76 mm in height [27], [28]. After compacted, the specimens were oven-dried and disparted into irregular lumps shape having 40 to 60 g each lump. Surendra et al. [29] used compacted cylindrical samples of 101.6 mm (4 inches) in diameter and 55.9 mm (2.2 inches) in height. The compacted specimens were cut into one-half of the height to produce two identical samples. These samples were tested in the slake durability apparatus. Previous studies have shown that the slake durability test was controlled by the specimen sizes, shape, and the number of cycles. This paper aims to investigate the slake durability of the stabilized siltstone with cement. The effect of cement on the durability was measured by dynamic wetting and drying cycles. The main objective of this investigation is to evaluate the fragment change and weathering type during the slake test and to determine the content-related cement to the slake-durability index of stabilized siltstones.

2 EXPERIMENTAL METHODS

2.1 Soil

The siltstone used in this study was collected from the toll road project at the Ungaran – Bawen section in Semarang, Central Java, Indonesia. According to the field of bedding, grain size analysis and clay mineralogy, samples were categorized as siltstone [30]. The slake-durability index (I_{d2}) of the samples was defined about 6.92%. Then, the samples were categorized as having very low durability according to the Franklin and Chandra criteria [14]. Series of index properties test were conducted on the samples as presented in Table 1. The soil samples consisted of about 51% fine-grained fraction, and about 49% coarse-grained fraction. The fine-grained fraction indicated a low plasticity soil. Then, the soil was categorized as A-6 group in associate with AASHTO soil classification system.

2.2 Cement

A general type of Portland cement (PC) manufactured by Holcim was used as the stabilizer in this study. The specific gravity of cement is 3.14, and the specific surface area was 3510 m^2/g. based on the Blaine method. The cement density was measured about 2950 kg/m^3. The PC fulfilled the requirement of ASTM C150 for Type I cement.

Table 1 Properties of the materials

Parameter	Value	ASTM Standards
Specific gravity, Gs	2.58	D854
Atterberg Limit		D4318
Liquid limit, LL (%)	38	
Plastic limit, PL (%)	22	
Plasticity index, PI (%)	16	
Standard Proctor Compaction:		D698
Maximum dry density, MDD (kN/m^3)	14.8	
Optimum moisture content, OMC (%)	25	
Soil fraction:		D422
Clay size (%)	12.5	
Silt size (%)	38.3	
Sand (%)	49.2	
Cement:		C188
Specific gravity, G_s	3.14	
Specific surface area (m^2/g)	3510	
Density (kg/m^3)	2950	

2.3 Experiment Design

A dynamic slake durability test was the primary test in this study. The soil samples were obtained by pulverizing the siltstones fragments. The soils were mixed by 2%, 5%, 7%, and 10% cement. Each stabilized specimen was subjected to weathering cycles up to five cycles of slaking (see Table 2). One cycle consisted of 24 hours oven-dried and about ten minutes submerged in water-bath (see schematic diagram in Fig. 1) during slaking. Before testing, the specimens were cured for seven days in the room temperature about 28ºC.

It was noted in this study that the specimen was prepared in a cylindrical mold of 34.5 mm x 34.5 mm. This approach is beneficial as it uses cylindrical shapes commonly used in testing triaxial test, which is easily formed, not easily broken, has a round shape, is uniform, and allow the mechanisms of weathering due to the rotation, sliding and crashing. The ASTM D4644-04 required that the weight of the fragment was 40 g to 60 g. Total of fragments and weight put in the slaking-drum was ten fragments with a total weight of 500 g to 550 g.

2.4 Specimen preparation

The siltstones samples were broken into small pieces, and then they were pulverized and sieved passing 4.75 mm (No. 4 sieves) size. An amount of

Table 2 Experiment and mixture design

Specimen	Code	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	5th Cycle
100% Soil (unstabilized)	SA	Y	Y	Y	Y	Y
98% Soil + 2% cement	SC2	Y	Y	Y	Y	Y
95% Soil + 5% cement	SC5	Y	Y	Y	Y	Y
93% Soil + 7% cement	SC7	Y	Y	Y	Y	Y
90% Soil + 10% cement	SC10	Y	Y	Y	Y	Y

Note: Y = tested

oven-dried soil was weighted about 550 g and mixed with water in the mixing batch thoroughly.

The water was added at its optimum moisture content (OMC) of the soil. For the stabilized soil, cement was added to the soil before mixing with water. The soil and cement mixture was stirred thoroughly in mixing batch until showing a homogenous matrix. The soil slurry was divided into ten smaller portions about 55 g. Then, the soil was transferred to the mold and compacted statically to the designed height of 34.5 mm. The specimen was dismantled from the mold and kept in an airtight plastic bag for seven days. Fig. 2 shows the compacted soil (Fig. 2a) and the group of specimens for slaking test (Fig. 2b).

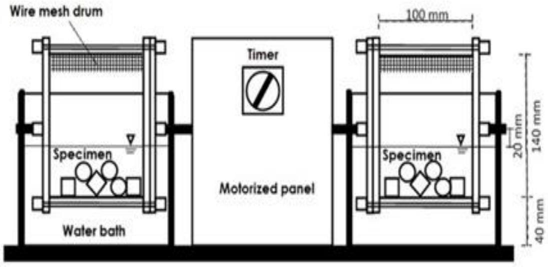

Fig. 1 Schematic diagram of the slake durability apparatus

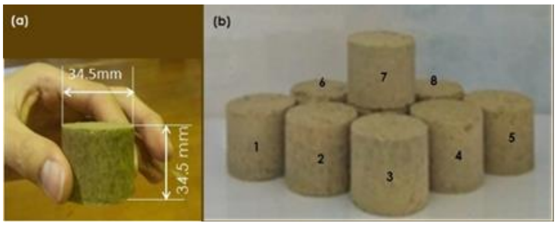

Fig. 2 (a) The specimen shape after compaction, (b) A set of specimen for dynamic slake-durability test

2.5 Testing Procedure

Slake durability index was determined according to the procedure of ASTM D4644. The slake durability apparatus consists of a drum with 140 mm in diameter and 100 mm in width (see Fig. 2). The drum with a screen opening of 2 mm (No. 10 sieves) was rotated in a water tub by an electric motor at a constant rate of 20 rpm. The slaking specimen consists of 10 pieces of the cylindrical specimen as prepared in the previous section. The specimens were oven-dried at 110±5ºC, then stored at room temperature (about 28ºC), and fill in the slaking drum. The drum was immersed in the water bath and was rotated for 200 revolutions or about 10 minutes. In the end, the material retained in the drum was oven-dried and weighed. The slake-durability index at the second cycle ($I_{d(2)}$) was defined as written in Eq. (1).

$$I_{d(2)} = \frac{W_{d(2)}}{B} \times 100 \tag{1}$$

where, $I_{d(2)}$ is slake-durability index at the second cycle; $W_{d(2)}$ is mass of retained drying specimen after the second cycle, B is mass of oven-dried specimen before the first cycle. Besides, the particles size distribution test was conducted at the end of each cycle to evaluate the physical change. The level of weathering was evaluated as the degree of slaking or slaking index (I_s) which was calculated by Eq. (2).

$$I_{s(n)} = \left(1 - \frac{W_{d(n)}}{B}\right) \times 100\% \tag{2}$$

where, $I_{s(n)}$ is degree of slaking at the n^{th} cycle; $W_{d(n)}$ is mass of retained oven-dried specimen after the n^{th} cycle.

3 RESULT AND DISCUSSION

3.1 The physical change due to slaking

Fig. 3 shows the physical changes of weathering due to the slake durability test. It is noted that the siltstones taken from quarry have high deterioration or low durability ($I_{d(2)}$ = 6.92%). Although the siltstones were compacted to its maximum dry density (SA specimen), the samples remained to be degraded easily to smaller fragments after the first cycle of the slaking test (see Fig. 3a). Fig. 3a shows that the weathered fragments degraded to uniform small particle sizes. Then, the weathering level of

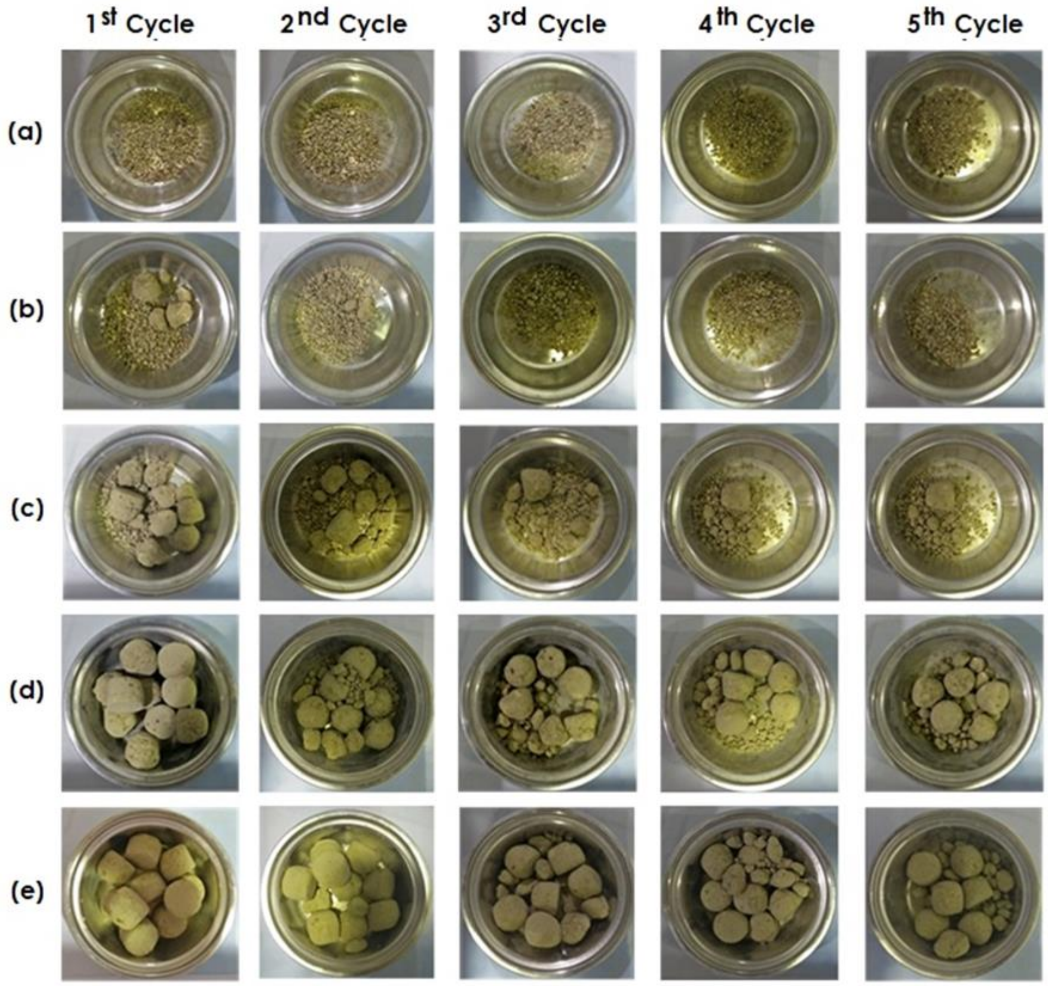

Fig. 3 Physical changes of the sample after drying cycle of the slake-durability test (a) SA, (b) SC2, (c) SC5, (d) SC7, and (e) SC10 specimens.

the soil was classified into type III fragment according to ASTM D4644.

The slake durability index ($I_{d(2)}$) of this compacted siltstones was measured about 12.76%. Based on the $I_{d(2)}$ value, compaction enhances the slake durability index from 6.92% to 12.76%. Hopkins [31] explained that compaction decreased the voids and reduced the permeability of a mudrock mass. This condition is important to prevent the intrusion of water in soil mass and minimize exposure of soil particles to water.

Fig. 3b to 3e shows the change of the physical size of the cement stabilized soil. In general, the addition of cement reduces the weathering of the siltstones. However, the addition of 2% cement (SC2) was insignificant to improve the durability. The stabilized soil almost totally degrades into small fragments except in the first cycle (see Fig. 3b). The weathering can be classified into Type III. Some fragments remain to have large particles after the first cycle by addition of 5% cement (Fig. 3c). However, the fragments degrade to small particle sizes after the second cycles. The amounts of larger fragments increase by the addition of 7% and 10% cement (Fig. 3d and 3e). Visually, the stabilized soils can be identified as Type II weathering. Interestingly, the fragments remain intact, and the initial shape becomes visible by mixing 10% cement (Fig. 3e). At the first cycle, abrasion during rotation of slaking drum reduces the specimen's surface. This characteristic is attributable to increasing the strength of soil due to cement stabilization [8].

In this experiment, the physical changes of the stabilized soil due to slaking test were evaluated by particle size distribution. In the cement stabilization mechanism, the cement modifies the fine-grained fraction to be a coarser grain [8], [10]. The percentage of coarse-grained after the slaking-wetting cycle is illustrated in Fig. 4. The figure shows that the percentage of coarse particles increases with the increasing cement content. Mixing the soil with 2% cement increases the coarse grain fraction considerably from 12% to 68% in the first cycle of slaking-drying. The coarse particles increase to 94% by mixing 10% cement. The result indicates that agglomeration takes place as the results of reaction accompanying soil-cement. The cement particles bind each other and wrap the soil particles during the hardening process. The inter-particle and intra-particle cementation form a harden and unchanged soil structure matrix [32], [33]. The secondary process of the soil-cement mixture produces supplementary cementation and increases bonding between particles. This process enhances strength and durability. This mechanism was confirmed by the previous research [9], [13], [34].

The deterioration due to climatic change of wetting-drying can be characterized by the degradation of soil particle to a smaller particle. The results in Fig. 4 also shows that the increase of slaking cycles decreases the presence of coarse-grains. The reduction of fragments sizes is due to the mechanism of rotation, sliding and crushing in the drum. In addition, the slaking cycles increase the broken fragments into fine-grain fractions. Soil mixed with 2% cement produces about 70% coarse grains fraction. However, the coarse particles decrease significantly to about 6% after five cycles of slaking. Increasing the cement dosage up to 10% results in about 60% coarse fraction after five cycles of slaking. This characteristic indicates that the dosage of cement is a controlling factor in the physical change of the soil during the weathering process. A large amount of cement was required to obtain successful stabilization [9], [13]. This study recommends that 7% of cement is suitable for soil modification.

3.2 Slake-durability index and degree of slaking

Slake durability measures potential deterioration of stabilized soil due to climatic change of the wetting-drying cycle. Fig. 5 shows the effect of cement on the slake-durability index ($I_{d(2)}$) of soil-cement mixtures. The correlation of cement content and the slake-durability index is likely sigmoidal-curve (**S**-curve). The change of $I_{d(2)}$ is slow initially, increase steeply, and then reaches an asymptotic value. Thus, the effect of cement on the slake-durability index of the soil-cement mixtures can be characterized into three zones: (1) inert zone, (2) improvement zone, and (3) stabilization zone.

The fundamental factor in soil stabilization is to ensure the supply of calcium provided by the stabilizer. The adequacy of calcium is important to establish a series of chemical reaction including cation exchange, flocculation and agglomeration, cementitious hydration, and pozzolanic reaction [13], [32], [33]. Adding a low cement content, e.g., 2% has made the effect on durability index less significant. At this inert zone stage, the binding effect of cement is induced by the cation exchange, which results in a small portion of agglomeration. The cement content was insufficient to produce further cementation reaction with soil. Increasing the cement content from 3% to 9% leads to a steep increase of the slake-durability index. As the cement content increases, the amount of hydration product also increases and upon hardening possesses a higher strength. When the gel hardens, the cementation welds the clusters and fills up the pore space. Increase in strength induced the slaking-durability, from which then its characteristic is designed as an improvement zone. Cementitious hydration consumed free moisture; hence an increase in the amount of cement leads to a reduction of water in the clay. If extra water is not available, a formation of large clay-cement clusters is introduced, and an intersection crack develops in the specimen [35]. At this stage, the growth of strength is relatively slower, and the process can be designated as stabilization zone. The stabilization zone was defined when the soil was mixed with 9% and more of cement. At the stabilization zone, the

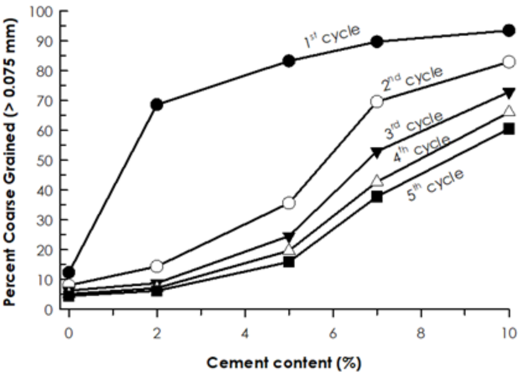

Fig. 4 Percent of coarse-grained of the stabilized soil due to slaking-drying cycles

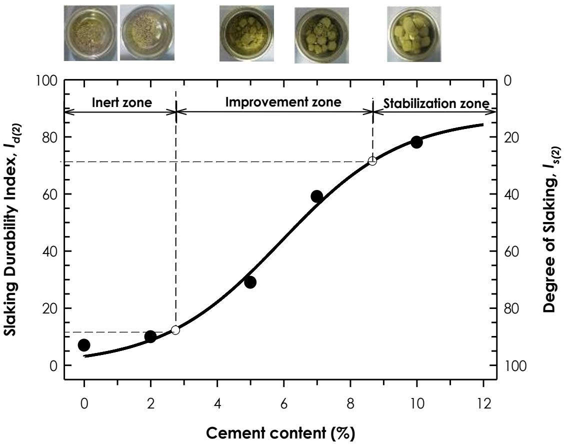

Fig. 5 The variation of slaking durability index ($I_{d(2)}$) with cement content

slake-durability index ($I_{d(2)}$) was higher than 70%, which was categorized as high-durability [14].

The effect of weathering in this study is defined as the degree of slaking (I_s). The effect of the slaking-drying cycle and the addition of cement on the degree of slaking is shown in Fig. 6. In general, the figure shows that slaking cycles ruins the stability of an intact specimen. For the unstabilized and stabilized soil, the degree of slaking increases as the number of slaking cycle increases. For the unstabilized specimen (SA), the degree of slaking is higher than 90% indicating a total or severely weathered after the first slaking cycle. The degree of slaking decreases as the cement content increases. The slaking index at the inert zone was 84% after the first cycle and increased to 94% after the fifth cycle. The result indicates that the addition of cement is less significant to retain the stability of soil particle. Addition of cement up to 7% (SC7) decreases the slaking index to 64% after the fifth cycle. The slaking index at the stabilization zone is measured 12%, 22%, 31%, 38%, and 42% for the 1st, 2nd, 3rd, 4th, and 5th slaking cycle respectively. Stavridakis and Hatzigogos [13] suggested a slaking index of 45% as criteria for satisfactory stabilization corresponds to the unconfined compressive strength provided for pavement design [9]. When the criteria of slaking index of 45% is applied, the addition of 10% cement satisfies the requirement for stabilization. Then, the stabilization zone provided in Fig. 5 is acceptable to determine cement content for stabilization.

Reducing the slaking index by cement stabilization can be explained traditionally. On this account, when water is mixed with cement, a hydration process takes place and followed by a hardening and pozzolanic reaction. The reaction produces a cementation compound of calcium – silicate – hydrate (CSH) and calcium – aluminate – hydrate (CAH). The compound gel of CSH and CAH binds adjacent cement granules during the hardening process and form a hardened soil structure matrix, which encloses soil particles [36], [37]. The water volume decreases during the hydration reaction and forms cementation material; the pore volume decreases as permeability decreases. The higher the cement content the stronger the ions exchange and the stronger the soil structure matrix decreasing the permeability [24], [36]. The lower permeability prohibits the sample from the wetting process in slake durability test, avoiding soil specimen to swelling and shrinkage, thus increasing its durability.

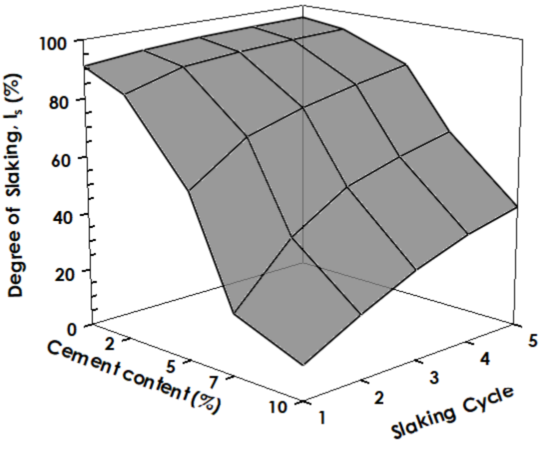

Fig. 6 Variation of the degree of slaking of the cement stabilized soil

4 CONCLUSION

This study examined the effect of cement stabilization on the slake durability behaviour of the compacted siltstone. Soil compaction and cement was the common method applied in roadwork. Thus, the compacted soil must meet the requirement of pavement system such as long-term durability to ensure the integrity and performance of the road. Slake durability test for the stabilized-compacted siltstones has been introduced in this study. The following concluding remarks can be summarized based on the foregoing discussion**.**

Compaction is a traditional method of soil improvement. Compaction of the soil at its maximum dry density and optimum moisture content enhances the slaking durability index ($I_{d(2)}$) by almost twice, 6.92% to 12.76%. The weathering level of the soil is classified into type III fragment. Slaking cycles degrade the siltstones into smaller fragments and fines particles. In cement stabilization, the percentage of coarse particles increases with the increasing cement content. A large amount of cement is required to obtain a successful stabilization, which is indicated by the fact that the remaining fragments are intact, and the initial shape is visible. This study recommends that 7% of cement is suitable for soil modification.

The weathering process can be defined by slaking index or degree of slaking, which measures the physical change of the siltstones. The degree of slaking increases as the number of slaking-drying cycle increases. On the contrary, the slaking index decreases as the cement content increases. When the criteria of slaking index of 45% is applied, addition of 10% cement satisfies the requirement for stabilization. The effect of cement on the slake-durability index ($I_{d(2)}$) of the soil-cement mixtures is slow initially, increases steeply, and then reaches an asymptotic value. At the stabilization zone, the slake-durability index ($I_{d(2)}$) is higher than 70%, which is categorized as the one with high-durability. The stabilization zone is defined when the soil is mixed with 9% and more of cement.

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6 REFERENCES

[1] Muhrozi and Wardani, S. P. R., Problem of High Embankment on Clay Shale at Semarang-Ungaran Toll Road STA 5+500 to 6+300, in *Geotechnical and Highway Engineering—Practical Applications, Challenges and Opportunities*, World Scientific, 2011, pp. 159-171.

[2] Irsyam, M., Susila, E., and Himawan, A., Slope failure of an embankment on clay shale at KM 97+ 500 of the cipularang toll road and the selected solution, in Proc. *Internat. Symposium Geotechnical Engineering, Ground Improvement and Geosynthetics for Human Security and Environmental Preservation*, Bangkok, Thailand, 2007, pp. 531-540.

[3] Alatas, I. M., Kamaruddin, S. A., Nazir, R., Irsyam, M., and Himawan, A., Shear strength degradation of Semarang Bawen clay shale due to weathering process, *J. of Tech.*, Vol. 77, No. 11, 2015, pp. 109-118

[4] Grainger, P., The classification of mudrocks for engineering purposes, *Quarter. J. of Eng. Geol. Hydrogeol.*, Vol. 17, No. 4, 1984, pp. 381-387, doi: 10.1144/GSL.QJEG.1984.017.04.13

[5] Sadisun, I. A., Shimada, H., Ichinose, M., and Matsui, K., Study on the physical disintegration characteristics of Subang claystone subjected to a modified slaking index test, *Geotech. Geol. Eng.*, Vol. 23, No. 3, 2005, pp. 199-218

[6] Smith, J. V. and Sullivan, L. A., Construction and Maintenance of Embankments using Highly Erodible Soils in the Pilbara, North-Western Australia, *Int. J. of GEOMATE*, Vol. 6, No. 2 (Sl. No. 12), 2014, pp. 897-902

[7] Supandi, Zakaria, Z., Sukiyah, E., and Sudradjat, A., The Correlation of Exposure Time and Claystone Properties at the Warukin Formation Indonesia, *Int. J. of GEOMATE*, Vol. 15, No. 52, 2018 pp. 160-167, doi: 10.21660/2018.52.68175

[8] Hartono, E., Wardani, S. P. R., and Muntohar, A. S., The effect of cement stabilization on the strength of the Bawen’s siltstone, presented at the Proc. 4th Int. Conf. of Rehabilitation and Maintanance in Civil Engineering (ICRMCE 2018), Solo Baru, Indonesia, 11-12 July 2018, 2018.

[9] Croft, J. B., The Problem in Predicting the Suitability of Soils for Cementitious Stablization, *Eng. Geol.*, Vol. 2, No. 6, 1968, pp. 397-424

[10] Herzog, A. and Mitchell, J. K., Reactions Accompanying Stabilization of Clay with Cement, *Highw. Res. Rec.*, Vol. 36, 1963, pp. 146-171

[11] Horpibulsuk, S. and Raksachon, Y., Effect of Cement Content on Strength and Microstructure of Cement Stabilized Clay, *Res. Dev. J.*, Vol. 19, No. 3, 2008, pp. 14-21

[12] Mohamedzein, Y. E.-A. and Al-Rawas, A. A., Cement-stabilization of sabkha soils from Al-Auzayba, Sultanate of Oman, *Geotech. Geol. Eng.*, Vol. 29, No. 6, 2011, p. 999, doi: 10.1007/s10706-011-9432-y

[13] Stavridakis, E. I. and Hatzigogos, T. N., Influence of Liquid Limit and Slaking on Cement Stabilized Clayey Admixtures, *Geotech. Geol. Eng.*, Vol. 17, 1999, pp. 145–154

[14] Franklin, J. and Chandra, R., The slake-durability test, *Int. J. of Rock Mech. Min. Sci.*, Vol. 9, No. 3, 1972, pp. 325-328, doi: 10.1016/0148-9062(72)90001-0

[15] Moradian, Z. A., Ghazvinian, A. H., Ahmadi, M., and Behnia, M., Predicting slake durability index of soft sandstone using indirect tests, *Int. J. of Rock Mech. Min. Sci.*, Vol. 47, No. 4, 2010, pp. 666-671, doi: 10.1016/j.ijrmms.2010.02.001

[16] Keaton, J. R. and Mishra, S. K., Modified slake durability test for erodible rock material, in *Scour and Erosion*, S. E. Burns *et al.*, (Eds.), American Society of Civil Engineers, 2010, pp. 743-748.

[17] Cano, M. and Tomás, R., Proposal of a New Parameter for the Weathering Characterization of Carbonate Flysch-Like Rock Masses: The Potential Degradation Index (PDI), *Rock Mech. Rock Eng.*, Vol. 49, No. 7, 2016, pp. 2623-2640, doi: 10.1007/s00603-016-0915-2

[18] Gautam, T. and Shakoor, A., Comparing the slaking of clay-bearing rocks under laboratory conditions to slaking under natural climatic conditions, *Rock Mech. Rock Eng.*, Vol. 49, No. 1, 2016, pp. 19-31, doi: 10.1007/s00603-015-0729-7

[19] ASTM D 4644–04: Standard Test Method forSlake Durability of Shales and Similar Weak Rocks, ASTM International, West Conshohocken, Pennsylvania, 2004.

[20] Agustawijaya, D. S., Modelled mechanisms in the slake-durability test for soft rocks, *Civ. Eng. Dimens.*, Vol. 5, No. 2, 2004, pp. 87-92

[21] Nakamura, Y. and Ishizuka, K., Comparison of Rock Durability Tests, *J. of Jpn. Soc. Eng. Geol.*, Vol. 25, No. 4, 1984, pp. 171-181

[22] Ankara, H., Kandemir, S. Y., and Çiçek, F., Compression of Slake Durability Index (SDI) Values of Sphere and Rounded Marl Samples, *Proc. Earth. Planet. Sci.*, Vol. 15, 2015, pp. 93-98, doi: 10.1016/j.proeps.2015.08.024

[23] Bryson, L. S., Gomez-Gutierrez, I. C., and Hopkins, T. C., Development of a new durability index for compacted shale, *Eng. Geol.*, Vol. 139-140, 2012, pp. 66-75, doi: 10.1016/j.enggeo.2012.04.011

[24] Crosta, G., Slake durability vs ultrasonic treatment for rock durability determinations, *Int. J. of Rock Mech. Min. Sci.*, Vol. 35, No. 6, 1998, pp. 815-824, doi: S0148-9062(98)00006-0

[25] Gautam, T. P. and Shakoor, A., Slaking behavior of clay-bearing rocks during a one-year exposure to natural climatic conditions, *Eng. Geol.*, Vol. 166, 2013, pp. 17-25, doi: 10.1016/j.enggeo.2013.08.003

[26] Heidari, M., Rafiei, B., Mohebi, Y., and Rastegarian, V., Prediction of long-term slake durability of clay-bearing rocks, *Geopersia,* Vol. 6, No. 1, 2016, pp. 35-43, doi: 10.22059/jgeope.2016.57820

[27] Ghosh, A. and Subbarao, C., Tensile strength bearing ratio and slake durability of class F fly ash stabilized with lime and gypsum, *J. of Mater. Civ. Eng.*, Vol. 18, No. 1, 2006, pp. 18-27, doi: 10.1061/(ASCE)0899-1561(2006)18%3A1(18)

[28] Chand, S. K. and Subbarao, C., Strength and slake durability of lime stabilized pond ash, *J. of Mater. Civ. Eng.*, Vol. 19, No. 7, 2007, pp. 601-608, doi: 10.1061/(ASCE)0899-1561(2007)19:7(601)

[29] Surendra, M., Lovell, C. W., and Wood, L., Laboratory studies of the stabilization of nondurable shales, *Transpor. Res. Rec.*, Vol. 790, 1981, pp. 33-41

[30] Dick, J. C., Shakoor, A., and Wells, N., A geological approach toward developing a mudrock-durability classification system, *Can. Geotech. J.*, Vol. 31, No. 1, 1994, pp. 17-27, doi: 10.1139/t94-003

[31] Hopkins, T. C., Shear strength of compacted shales, Research Report No. UKTRP-88-1, Kentucky Transportation Center Research, University of Kentucky, 1988.

[32] Croft, J. B., The Structrures of Soils Stabilized with Cementitious Agents, *Eng. Geol.*, Vol. 2, No. 2, 1967, pp. 63-80

[33] Prusinski, J. and Bhattacharja, S., Effectiveness of Portland cement and lime in stabilizing clay soils, *Transpor. Res. Rec.*, Vol. 1652, 1999, pp. 215-227, doi: 10.3141/1652-28

[34] Xuan, D. X., Houben, L. J. M., Molenaar, A. A. A., and Shui, Z. H., Mechanical properties of cement-treated aggregate material – A review, *Mater. Des.*, Vol. 33, 2012, pp. 496–502, doi: 10.1016/j.matdes.2011.04.055

[35] Horpibulsuk, S., Rachan, R., Chinkulkijniwat, A., Raksachon, Y., and Suddeepong, A., Analysis of strength development in cement-stabilized silty clay from microstructural considerations, *Constr. Build. Mater.*, Vol. 24, 2010, pp. 2011–2021, doi: 10.1016/j.conbuildmat.2010.03.011

[36] Chew, S., Kamruzzaman, A., and Lee, F., Physicochemical and engineering behavior of cement treated clays, *J. of Geotech. Geoeviron. Eng.*, Vol. 130, No. 7, 2004, pp. 696-706, doi: 10.1061/(ASCE)1090-0241(2004)130:7(696)

[37] Kang, G. O., Tsuchida, T., Kim, Y. S., and Baek, W. J., Influence of Humic Acid on the Strength Behavior of Cement-Treated Clay during Various Curing Stages, *J. of Mater. Civ. Eng.*, Vol. 29, No. 8, 2017, doi: 10.1061/(asce)mt.1943-5533.0001919