Civil Engineering and Architecture 12(2): 1057-1068, 2024 http://www.hrpub.org
DOI: 10.13189/cea.2024.120229

Effect of Slaking Cycles on Weathered Rock Material

Andius D. Putra

Department of Civil Engineering, Faculty of Engineering, University of Lampung, Bandar Lampung, 35145, Lampung, Indonesia

Received June 4, 2023; Revised October 5, 2023; Accepted December 21, 2023

Cite This Paper in the Following Citation Styles

(a): *[1] Andius D. Putra , "Effect of Slaking Cycles on Weathered Rock Material," Civil Engineering and Architecture, Vol. 12, No. 2, pp. 1057 - 1068, 2024. DOI: 10.13189/cea.2024.120229.*

(b): *Andius D. Putra (2024). Effect of Slaking Cycles on Weathered Rock Material. Civil Engineering and Architecture, 12(2), 1057 - 1068. DOI: 10.13189/cea.2024.120229.*

Abstract Differential settlements, a geotechnical concern, have been documented in earth fills constructed from weathered rock materials. The primary factor contributing to the problem is often seen as the progressive deterioration of the material because of weathering. Weathered rocks undergo a process of fragmentation into smaller particles as a result of repeated cycles of wetting and drying. The observed behaviour can be classified as a mechanical-hydraulic weathering process commonly referred to as "slaking". This study examines the phenomenon of rock deformation caused by slaking in weathered conditions. A sequence of unidimensional slaking experiments was conducted. During the experiment, a one-dimensional compression test was conducted on a desiccated sample. The compression was applied vertically in incremental steps, first at 9.8 kPa and thereafter increasing to 19.6, 39.2, 78.5, 157.0, 314.0, 628.0, and 1256.0 kPa. The wetting and drying processes were iterated while maintaining a compression level of either 314.0 or 1,256 kilopascals (kPa). The duration of each loading cycle was decided to be 30 minutes, based on the observation that the compression of the specimen occurred promptly and that there were no remarkable volumetric changes throughout the compression phase. The analysis of the test findings indicated that the sample's particle size distribution was widened as a result of repetitive wetting and drying cycles, and it was seen that notable irreversible compression occurred. Additionally, this study investigates potential strategies to mitigate the distortion caused by slaking in embankments composed of crushed weak rock. The research revealed that the application of high compression pressure initially, followed by a controlled release to a certain pressure prior to the initiation of the slaking cycle, resulted in the reduction of mudstone.

Keywords Weathered Rocks, One-dimensional Compression, Slaking, Particle Size Distribution, Deformation

1. Introduction

Mudstone is composed of fragmented and structurally compromised rock, commonly employed in the construction of embankments. One of the factors contributing to its extensive utilization is its ready accessibility in substantial quantities as waste material generated from significant construction projects. The primary concern regarding mudstone is its susceptibility to slaking or softening upon immersion in water, resulting in a significant reduction in its strength. Slaking refers to a cyclic process involving the alternation of soaking and drying. This phenomenon may alternatively be denoted as a slaking cycle. Rocks, particularly those that possess clay minerals, exhibit a tendency to undergo deformation during the soaking period, subsequently followed by contraction during the subsequent drying phase. The introduction of water into the pores of a rock induces an expansion in volume, leading to the generation of tensile strains that subsequently cause the formation of fractures [1]. The presence of microcracks and their subsequent spread contributes to a further rise in porosity. The phenomenon of alternating discussion and drying within the rock material comprising the road body is typically attributed to the ingress of water through fissures in the rigid stratum or variations in the hydraulic gradient. The phenomenon of wetting and drying induces alterations in volume, resulting in deformation. Empirical investigations have demonstrated that the process of slaking possesses the ability to disintegrate solid rock. Certain investigations have demonstrated that water with a specific salinity level has reduced effectiveness in slaking compared to pure water, contingent upon the type of rock [2]. Additionally, empirical studies have demonstrated that the attainment of maximum moisture content can occur expeditiously. One crucial aspect to consider is that the efficacy of slaking is governed by the duration of the drying process. The observed behavior can be classified as a mechanical-hydraulic weathering mechanism referred to as slaking cycles. The recurrent occurrence of the weathering process can result in the gradual weakening and subsequent loss of structural integrity of the material, potentially resulting in failures. The documentation of experiments examining the mechanical behavior of sedimentary rocks in relation to weathering and softening caused by slaking is currently lacking [3]. The intensification of clay-mineral fabric in mass transport deposits (MTD) of mudstones is believed to be caused by the process of remolding and shearing following mass movement. This process leads to the mechanical disaggregation of initially deposited clay mineral flocs, overcoming the physio-chemical forces of attraction. The acknowledgment of improved microfabrics holds significant ramifications for seismic anisotropy, as well as for the movement of shallow fluids [4]. Regarding the phenomenon of mudstone softening, it has been observed that certain deposits exhibit substantial strength reductions, reaching up to 80%. The observed level of strength decline is substantial and requires significant reduction. In their study on the degradation process of bedrock (specifically mudstone) in areas prone to landslides, the researchers cited in reference [5] identified the primary factor responsible for this phenomenon as the presence of softening material. The investigation of crushed rocks subjected to saturated circumstances showed a significant reduction in strength as a result of granular breakdown produced by water. Three mechanisms have been recognized as contributing to the process of slaking in soils. These mechanisms include the dispersion of soil particles, the swelling generated by stress release and water absorption, and the tensile tensions that arise from the compression of entrapped air during water absorption (9).

Although laboratory methods have been devised to assess durability, no significant link has been shown between the laboratory findings and straightforward field tests. Consequently, this research study has introduced a simple field test. During the wetting and drying process, it is seen that when mudstone reaches a state of dryness, air is pulled into the intra-granular pores, resulting in the development of a significant suction pressure. Under conditions of acute desiccation, the majority of the voids are occupied by air. When mudstones are abruptly submerged in water, the macro-pores are promptly saturated with water. Capillary forces arise as a result of suction, leading to the compression of air within the micro-pores [7]. The occurrence of tensile failure in the mineral skeleton along the weakest pathways can lead to an increase in the exposed surface area. The air pressure generated within the macro-pores is contingent upon the capillary pressures, which are in turn influenced by the surface tension of the water and the radius of the pore [6, 11]. The potential slaking of shales or mudstone embankments has been evaluated by the observation of the compaction effect [9, 10]. In addition to compaction, experiments on the durability of slakes were performed in order to figure out the resistance of unstable rocks to weathering, including shales, mudstones, and siltstones. These tests involved subjecting the rocks to several wetting and drying cycles under unconfined conditions. The study showed that the slaking cycles had a substantial impact on the deterioration process, leading to the development of grading [4].

The matter at hand is of utmost importance and necessitates prompt attention in order to mitigate the ongoing deterioration. It is imperative to identify and implement suitable strategies to curb this degradation. The most suitable approach to address this matter entails the implementation of laboratory tests in order to gain a comprehensive understanding of the slaking process and its associated implications. To gain insights into the enduring ramifications of diverse natural phenomena and earth structural concerns associated with mudstone, it is imperative to enhance comprehension of the deformation characteristics induced by slaking. Hence, the objective of this study is to investigate the slaking behavior mechanism by the utilization of one-dimensional compression slaking cycle experiments. Additionally, a proposed approach to mitigate the challenges associated with mudstone in embankment construction will be presented.

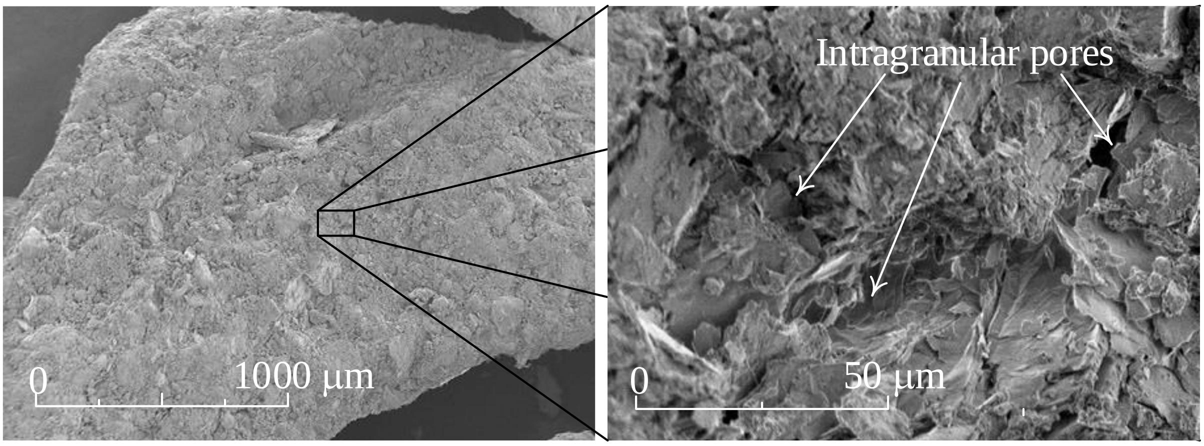
2. Material and Methods

2.1. Weathered Rocks' Materials

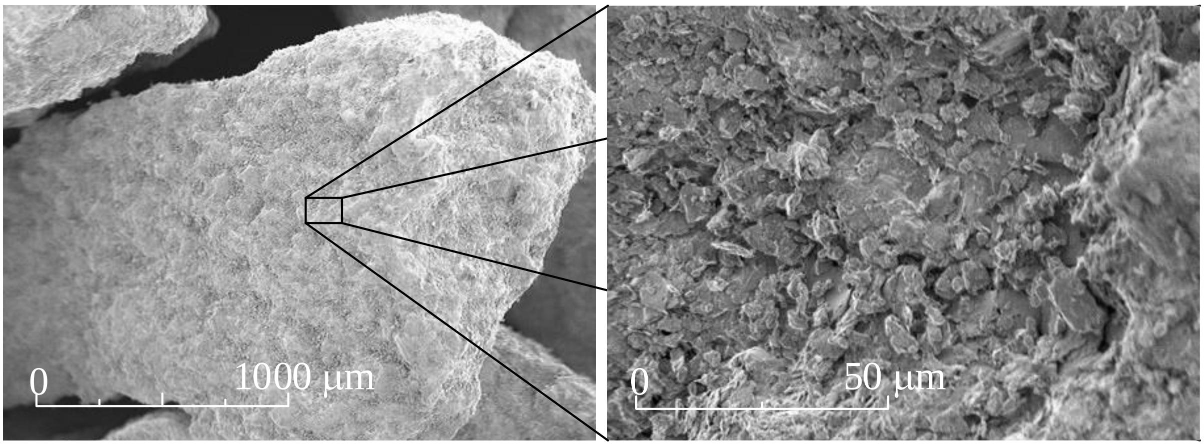
Weathering refers to the process by which rocks undergo changes as a result of their prolonged contact with various environmental elements, including air, water, and organic fluids. It is widely acknowledged that no rock exhibits stability or immunity to the process of weathering. This paper aims to examine various materials that have been included for analysis subsequent to the prior study [3]. The experimental investigation in this study involved the utilization of Kakegawa mudstone and Hattian Bala mudstone as the selected materials. In this study, Toyoura sand was employed as an unyielding comparator material. The comprehensive characteristics of the geo-material investigated in this study have been succinctly outlined in Table 1. In the meantime, the examination of the mudstone specimens' physical characteristics was conducted using a scanning electron microscope (SEM), as depicted in Figure 1.

Table 1. General properties of geo-materials

Original mudstone specimen	Particle density, ρ_s	Max void ratio e_{max}	Min void ratio e_{min}	Geological period
Kakegawa	2.65	1.83	1.29	Neogene
Hattian Bala	2.75	1.09	0.79	Neogene
Toyoura sand	2.65	0.98	0.61	--



(a) Kakegawa mudstone



(b) Hattian Bala mudstone

Figure 1. The surface condition of Kakegawa and Hattian Bala mudstones with different magnifications (left: 50x and right: 1000x)

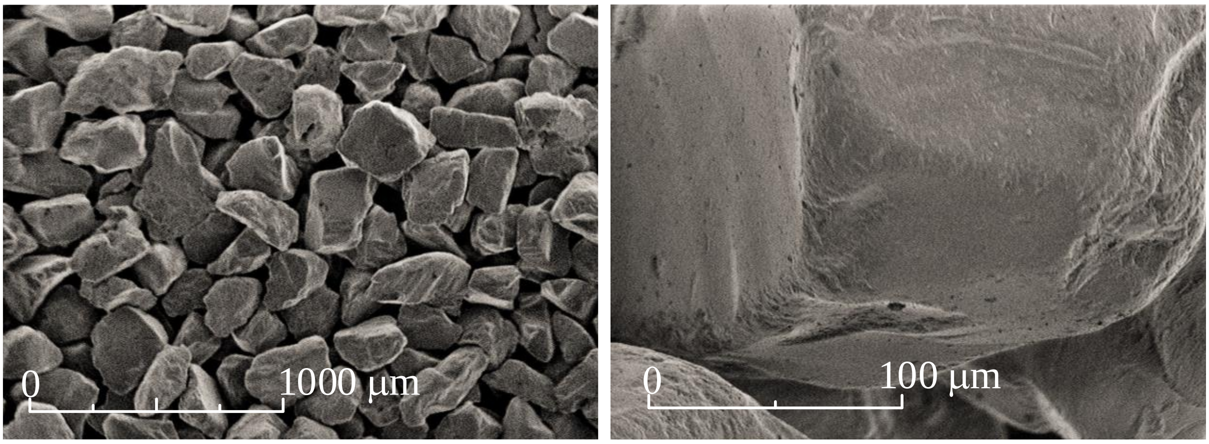


Figure 2. Toyoura sand surface morphology as un-slakable comparative material

In contrast to Hattian Bala mudstone, the Kakegawa mudstone (Figure 1(a), right) displayed distinct intra-granular pores. In contrast, Figure 2 illustrates that Toyoura sand has a more refined particle surface. The Kakegawa mudstone may be traced back to its source near the Daiichi Tokai (Tomei) highway. The region has multiple instances of landslides during the period of increased precipitation, leading to the hypothesis that these events are linked to the presence of mudstone. The Hattian Bala mudstone is deposited at a naturally occurring barrier about 3.5 kilometers upstream of the Karli River [9]. The assessment of particle size distribution transformation is a crucial metric for studying the impact of weathering-induced deformation. Moreover, in the course of the experiments, the particle size distribution is manipulated to traverse through sieve number 2 while being captured by sieve number 20, including particle size diameters ranging from 2.00 to 0.85 mm.

2.2. The Evolution of Grading Size

Changes in the particle size distribution (PSD) have been demonstrated as a result of the development of grading, as demonstrated by the index of grading (I_G) [1, 3]. The increment of I_G is directly proportional to the breakage parameter B_r. The B_r value is determined by calculating the ratio between the areas of segments ABCD and ABCF, as depicted in Figure 3. While both indices possess a numerical range of 0 to 1, it is important to note that Hardin's breakage parameter, Br, does not encompass the concept of limiting or critical grading. Multiple experimental pieces of data support the establishment of a limiting grading on the breakage parameter (B_r).

This study aims to ascertain the evolution of grading resulting from wetting and drying cycles, employing a methodology akin to that employed for determining the grading index of I_G in particle crushing. Hence, it is imperative to assess the particle size distribution subsequent to the processes of crushing and slaking, thereby ensuring comprehensive evaluation at the conclusion of experimentation.

In this study, particle size distribution analysis was conducted during several stages, including the final compression and slaking cycle. The alteration in particle size distribution is elucidated by the particle distribution curve. This experiment aims to evaluate the impact of grading variation resulting from slaking on compression behavior.

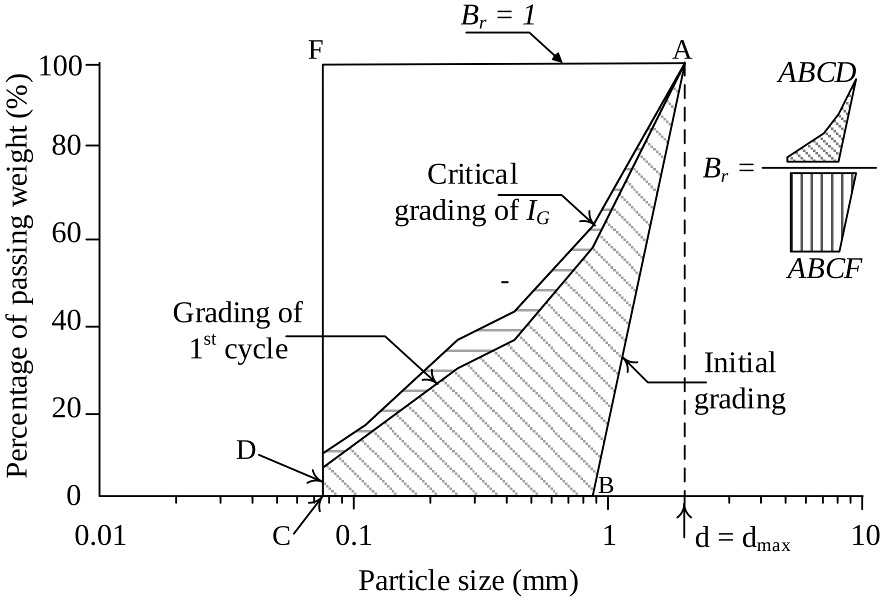


Figure 3. The Breakage Parameter (B_r)

2.3. Weathering Under 1D Compression Slaking

Figure 4 illustrates the experimental setup that was used for this inquiry and presents its configuration to the reader. The system includes a measuring system, a loading system, and a system for the wetting and drying routes. The container for the specimen was a rigid construction in the shape of a cylinder constructed of steel. It had a diameter of 60 millimeters and a height of 40 millimeters. The top loading plate and the bottom loading plate of the container both have porous stones placed on them. The pneumatic air cylinder was used to adjust the vertical load, and a load cell was used to quantify the magnitude of this stress. Both of these components were operated simultaneously. At the same time, a linear variable differential transformer (LVDT), also known as a displacement transducer, was deployed in order to quantify the vertical displacement that took place throughout the course of the test.

The wetting and drying line was linked to the steel ring chamber, which included a porous material affixed to the bottom plate and was also connected to the line's input. The fundamental constituents involved in the wetting phenomenon were a solution of carbon dioxide and air-free distilled water. The vessel utilized for containing the distilled water was attached to a vacuum pump in order to expedite the de-airing process. Nevertheless, during the process of dispensing water to the specimen, the tank remained unclosed, allowing it to be exposed to the ambient air in its vicinity. The drying process had two distinct lines: a drainage channel, which required exposure to atmospheric pressure, and an input line, which was connected to a tank containing compressed air that had undergone drying through the use of silica gel (see Figure 4). Furthermore, it was necessary to expose the drainage canal to air pressure.

The experiment was started by putting the specimen that had been dehydrated into the confining chamber that had a density level that was somewhere in the middle. After that, the load cell and the LVDT gauge were both mounted and given their initial readings. The original height of the specimen was measured in order to provide an accurate reading of its initial void ratio. After that, a pneumatic air cylinder and loading rod were utilized in order to apply a progressively increasing amount of vertical force on the specimen. The levels of vertical stress that were applied in phases were 9.8, 19.6, 39.2, 78.5, 157.0, 314.0, and 1256.0 kPa respectively. The duration of each loading cycle was determined to be thirty minutes due to the fact that it was noticed that the compression of the specimen proceeded in a timely manner and that there were no major volumetric changes observed during the course of the compression phase. After reaching a certain amount of specified vertical tension, a cycle of wetting and drying was performed while ensuring that the degree of vertical stress remained constant throughout the process. The wetting technique started by slowly permeating carbon dioxide into the specimen while keeping the void pressure constant for a period of thirty minutes in order to remove any traces of air that might have been present.

Subsequently, the distilled water was introduced into the specimen by capitalizing on a minor disparity in water level between the water tank and the container holding the specimen (referred to as h1 in Figure 4), until the specimen achieved complete submersion. Following a 6-hour period of submerging the specimen, the drying process was initiated by removing the excess water from the specimen for a duration of 30 minutes. This was achieved by allowing the water to drain through a tiny variation in water level, denoted as h2 in Figure 4. Silica gel packs were strategically placed around the steel cylinder of the specimen container, and a controlled flow of dry air was allowed to infiltrate through the specimen for a duration of 48 hours, ensuring thorough desiccation. During the course of this experiment, the cycle of soaking and drying was repeated three times, and each time, the volumetric behavior was observed. Following the end of the last drying operation, the specimen was dried in an oven and then sieved afterward. The only movements involved in the sieving process were horizontal circular motions, and there was no tapping impulse at any point in the process. By evaluating the differences in the distribution of particle sizes over each cycle, we were able to calculate the grading change ratio.

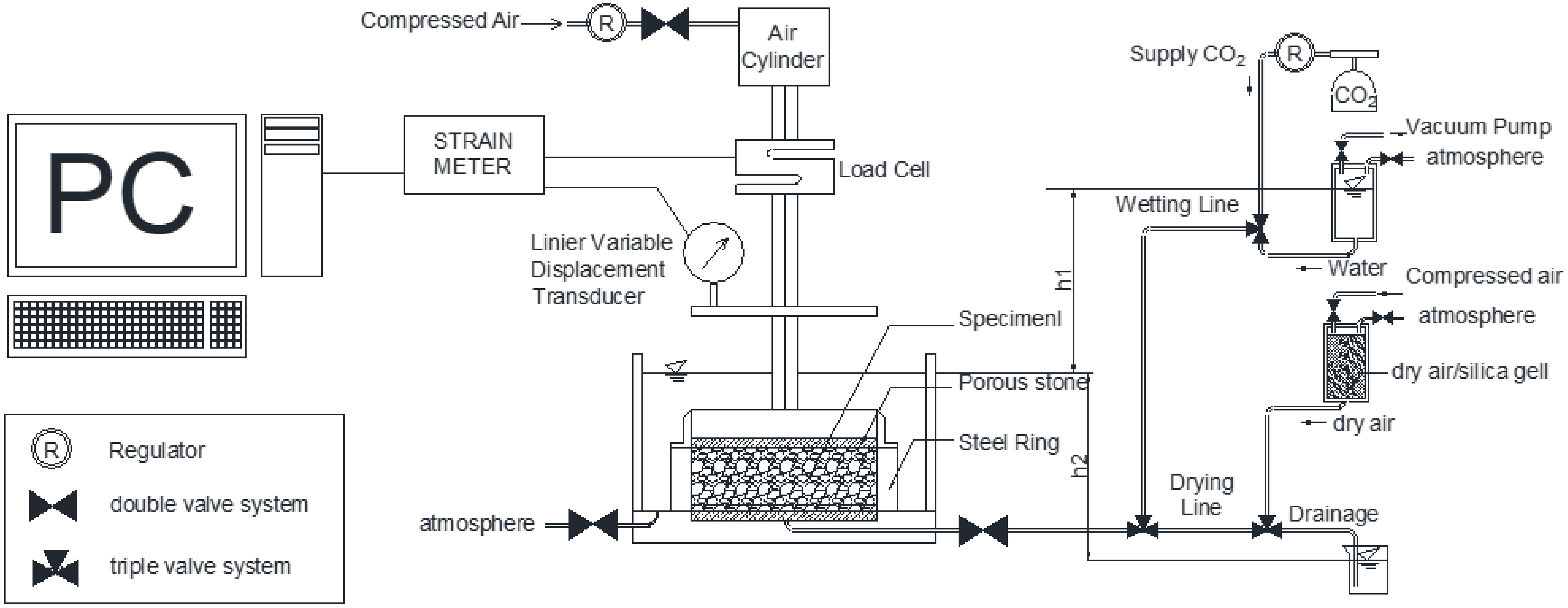


Figure 4. Schematic set-up of the experiment for one-dimensional compression slaking

3. Result and Discussions

In order to analyze the change in grading, it is important to represent the particle size distribution of the initial condition following compression, encompassing different quantities of wetting and drying cycles, as depicted in Figure 6. Figures 5(a) and 5(b) depict the alterations in the distribution of particle sizes resulting from multiple 1D compression slaking cycles applied to Kakegawa mudstone and Hattian Bala mudstone. These cycles were conducted under varying vertical effective stresses (σ_v') of 314 and 1256 kPa, respectively. An alteration in the grading size distribution of Kakegawa mudstone and Hattian Bala mudstone has been reported to take place under conditions of compression; further modifications become apparent when the sediments undergo wetting and drying treatments. The correlation between elevated stress levels and the advancement of grading as a result of particle disintegration is readily seen. Both mudstone samples exhibited changes in particle size distribution during the process of soaking and drying, however, the magnitude of these changes varied between the different types of mudstone. The Kakegawa mudstone exhibited a notable alteration in the distribution of particle sizes, potentially attributable to the presence of intra-granular pores. The examination of the particle size distribution also indicated that the mudstone specimens maintained a very consistent maximum particle size throughout the one-dimensional compression slaking tests.

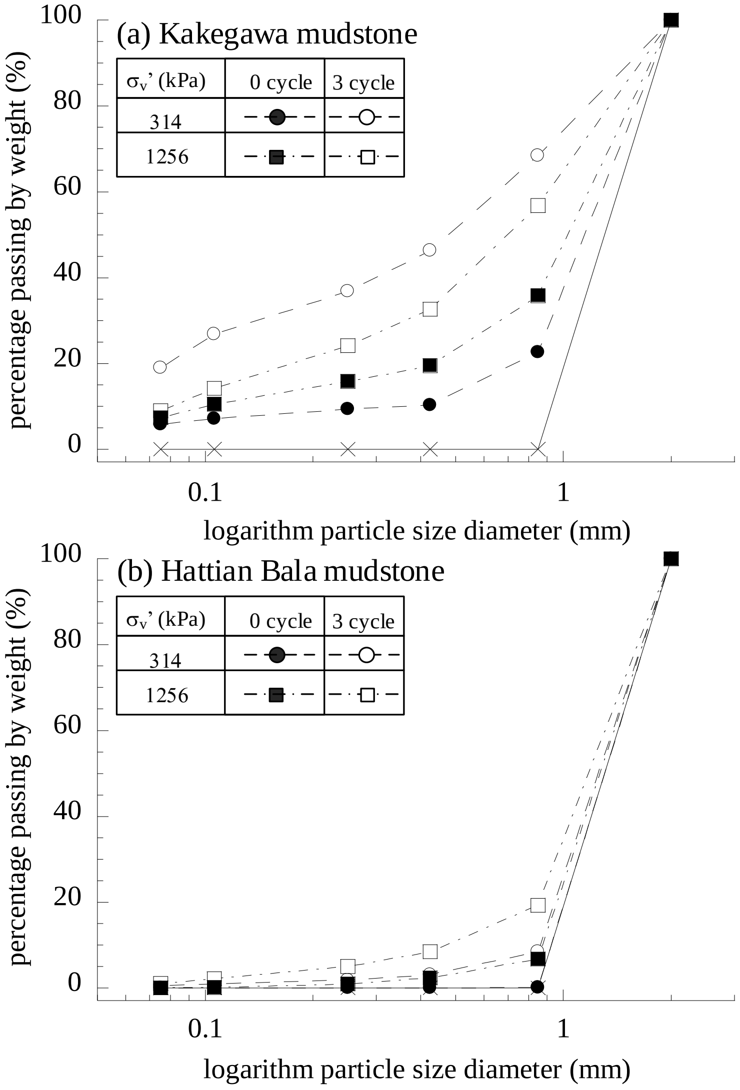


Figure 5. The alteration of particle size distribution occurs as a result of compression and slaking cycles

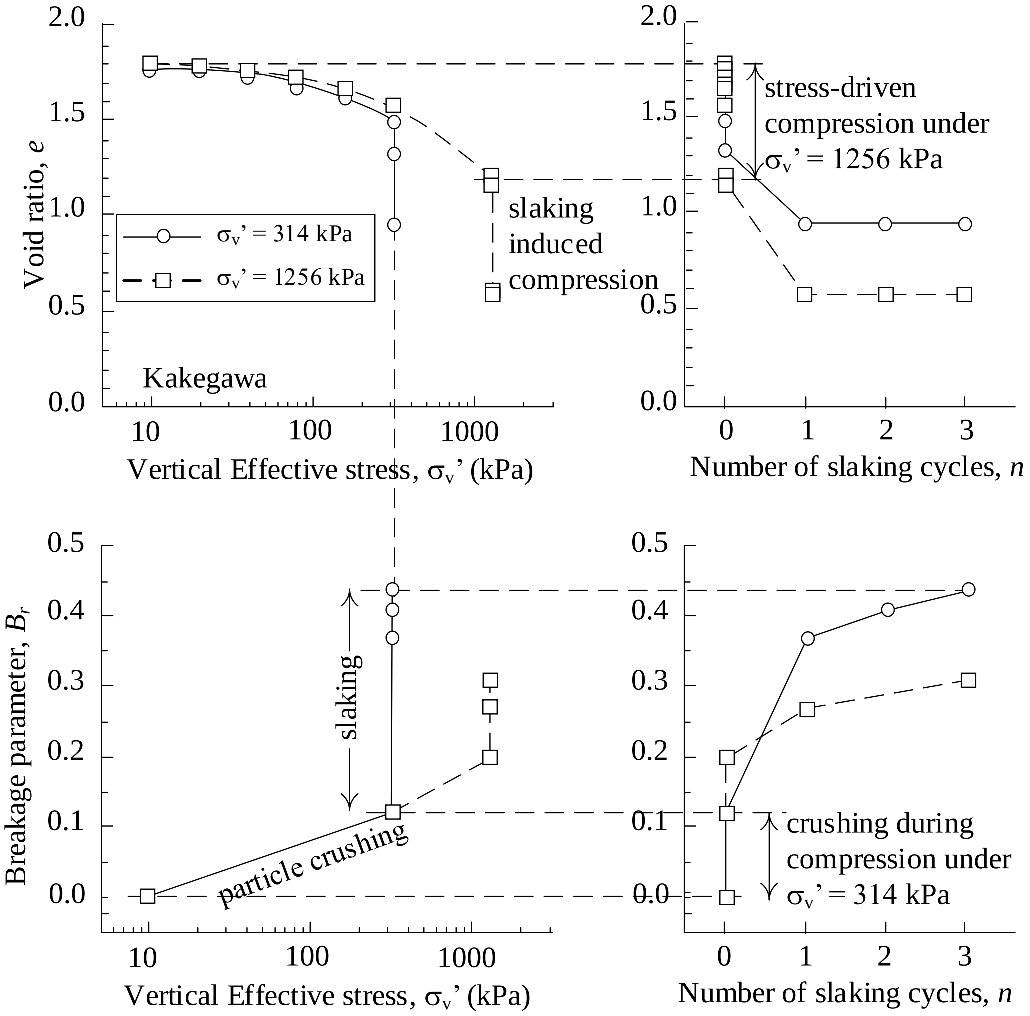


Figure 6. Observations on the effects of weathering on the grading size of Kakegawa mudstone subjected to a 1D compression slaking test

Hence, it is logical to deduce that the fragmentation of soil particles is a consequence of compression and the alternating wetting and drying cycles. Consequently, the resulting broken particles contribute to an augmented ratio of fine particles, which serve to occupy the empty spaces between larger particles, while the maximum particle size remains largely unaltered.

In the interim, it is observed that the compression line depicted in Figures 6(a) and 6(b) exhibits a gradual inclination, thereby substantiating the occurrence of particle crushing during the compression process. Following the soaking and drying process, the Br value exhibited a rise from 0.12 to 0.44, as depicted in Figure 6(c). Additionally, the specimen underwent substantial compression, resulting in a void ratio reduction above 0.9. Regarding the Hattian Bala mudstone, the findings, which have been succinctly presented in Figure 7, indicate that there was no noteworthy change in Br (bromine) levels during the wetting and drying process, and the volumetric compression, as indicated by the decrease in void ratio e, was also not substantial. It was determined that the mudstone experiences significant compression as a result of slaking caused by repeated wetting and drying under a constant vertical effective tension. To mitigate the deformation characteristics of weathered rock, it is imperative to initiate compression by subjecting the particles to crushing. There is a prevailing belief that fine particles have the potential to occupy empty spaces within granular materials, including intra-granular pores.

Consequently, the process of loading and unloading was executed. During the experimental procedure, a series of mudstone specimens were subjected to compaction and preparation, each with varying initial void ratios. Specifically, the void ratios for the respective cases were as follows: 1.54 for case 4, 1.34 for case 5, 1.43 for case 6, and 1.55 for case 7. The experiment commenced by incrementally applying compressive force ranging from 9.8 kilopascals (kPa) to 1256 kPa, with each compression lasting for a length of 30 minutes. The initial step involved the crushing of the material. Upon completion of the loading phase, the subsequent unloading phase persisted until reaching a pressure of 314 kPa. The findings from the analysis of particle size distribution (PSD) indicated a comparable line or curve, as depicted in Figure 8. These results provide evidence that variations in the initial void ratio did not have a substantial impact on the alterations in grading.

Furthermore, the depicted curve exhibits a line that bears resemblance to the results obtained from a compression slaking test involving a single cycle of wetting and drying, as well as loading at a magnitude of 314 kPa. Figure 9 demonstrates the alterations in grading subsequent to the loading/unloading stages and slaking cycle. Upon meticulous examination, it becomes evident that a slight expansion takes place subsequent to the unloading process to 314 kPa; nonetheless, it appears that this expansion has not had any discernible impact on the void ratio. The observed variation in void ratio, resulting from varying compaction levels, led to a minor reduction in volume compression caused by slaking during the wetting and drying process following the application of stress history (see Figure 9(a)). Significant progress has been made in mitigating the potential deformation of mudstone material. Figures 9(c) and 9(d) demonstrate the breakage parameter resulting from the application and removal of pressure, followed by a cycle of wetting and drying.

In advance, the dashed line represents the estimated value of the breakage parameter resulting from the stress history of the loading and unloading process, as well as the particle crushing transformation. There is a potential occurrence of particle crushing during the application of high pressure, which may be indicated by the observed changes in grading, namely the increasing presence of fine-grained material. The mudstone specimen experiences an increase in density with the application of strong compressive stress, leading to the filling of voids by the material including fine grains. Figure 9(a) demonstrates that the volumetric compression experienced during the process of cyclic wetting and drying is reduced by approximately 50% compared to the typical compressive slaking test. This phenomenon can be attributed to the application of a high compressive stress of 1256 kPa, which resulted in a rise in Br to around 0.15 during the compression process.

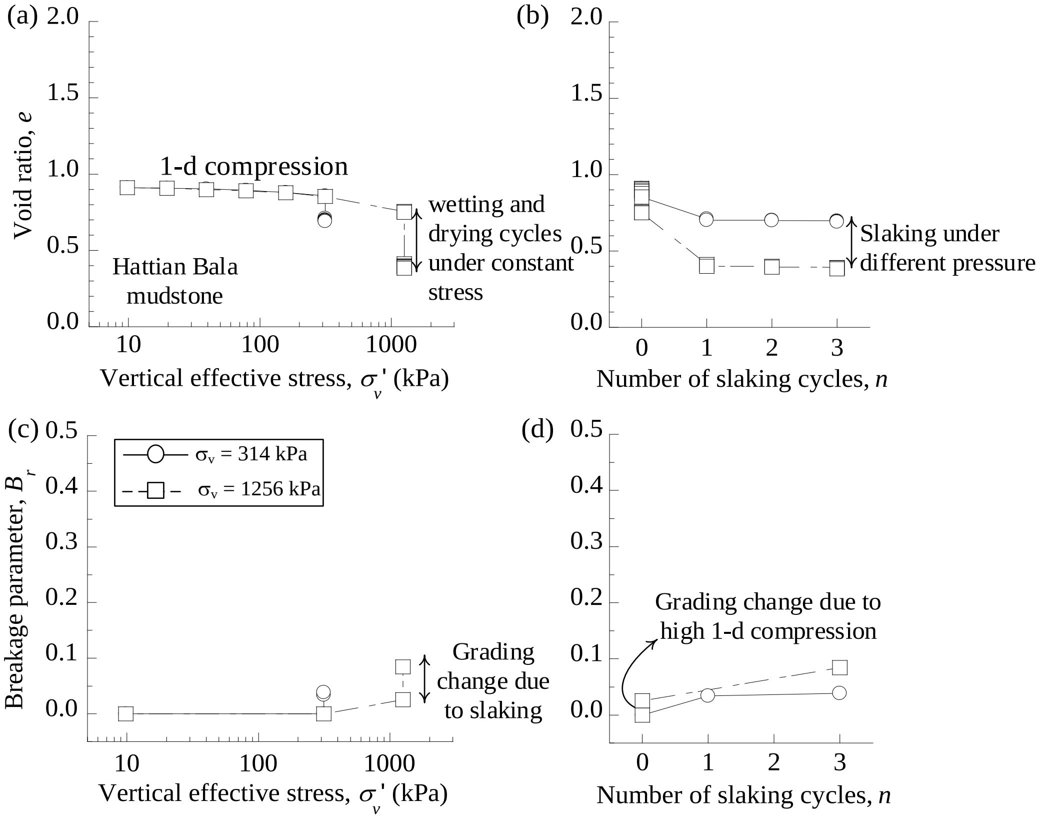


Figure 7. Observations on the effects of weathering on the grading size of Hattian Bala mudstone subjected to a 1D compression slaking test

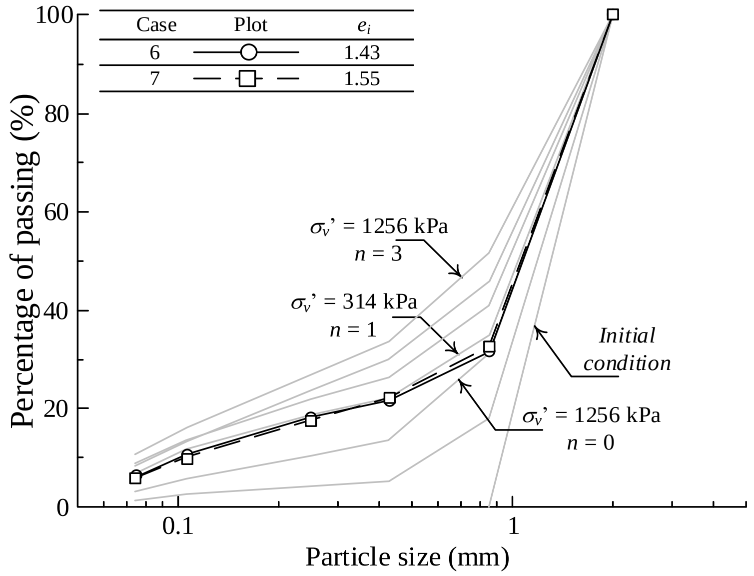
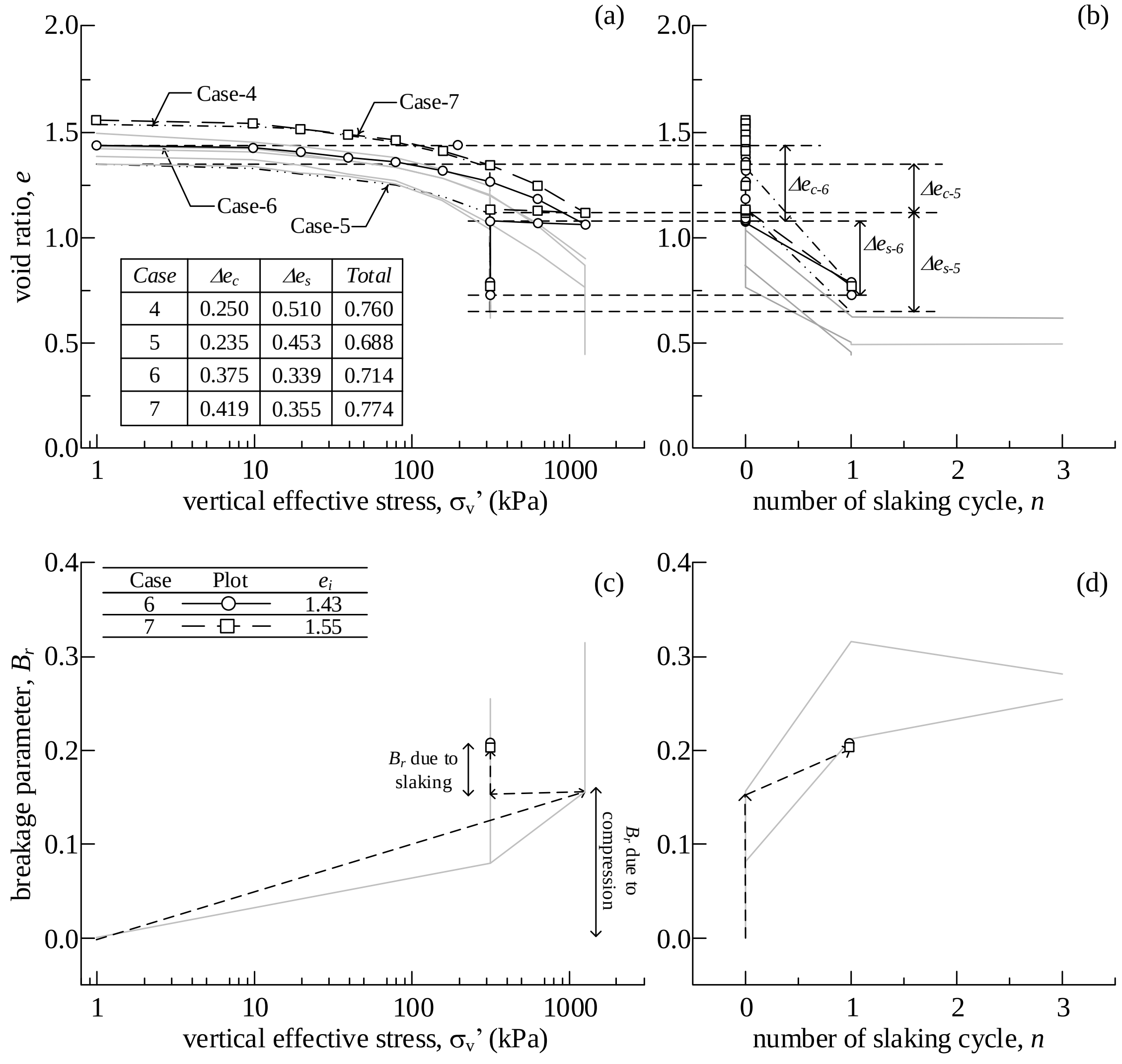


Figure 8. Varying particulate size distribution subsequent to the implementation of a stress history condition



Case	Δe_c	Δe_s	Total
4	0.250	0.510	0.760
5	0.235	0.453	0.688
6	0.375	0.339	0.714
7	0.419	0.355	0.774

Figure 9. Countermeasures of slaking issue by applying stress history schemes

Furthermore, the cyclic wetting and drying process led to a reduction in the change in particle size, specifically the quantity of increase in Br. The volumetric compression along the swelling line was enlarged as a result of the unloading process, leading to the separation from the typical consolidation line and resulting in over-consolidation.

This study has identified that when employing earth construction techniques involving materials with slaking properties, it is crucial to prioritize roller compaction during the embanking process. This practice promotes particle crushing, effectively managing the occurrence of slaking during cyclic wetting and drying cycles, thereby minimizing the likelihood of volumetric compression. In the context of mudstone embankments, one potential construction strategy to mitigate potential deformation involves considering the stress history of loading and unloading throughout the construction process.

4. Conclusions

Within the scope of this inquiry, a series of compression slaking tests in a single dimension were carried out. The purpose of this research was to gain a better knowledge of the mechanical repercussions that would occur on weaker rock formations if they were subjected to alternating periods of wetness and drying. In addition, in order to demonstrate the findings of this inquiry, scanning electron microscopy (SEM) was used to investigate the surface morphology of the weak rock particles, which magnified their inherent dimensions. This was done in order to demonstrate the findings of this investigation.

Because of the existence of intra-granular pores inside the particles, the surface morphology of the mudstone was observed to have different variations in slaking and deformation properties. This can be related to the fact that the particles include intra-granular pores. The exposing of intra-granular pores can make it easier to notice grading evolution brought on by slaking. This can be helpful in a number of situations. The mechanical characteristics of fragile rocks undergo an indelible alteration due to the differences in density and compaction, resulting in this outcome. In addition, the changes in the distribution of particle sizes that take place as a direct result of grading that takes place during compression might make rocks that already have a low strength more susceptible to being compressed. Even if the effective stress has not changed, this phenomenon can still be seen because the wetting and drying cycles cause a significant amount of compression. It is possible to adequately quantify the phenomenon of particle size distribution evolution under constant limited stress, in which the maximum particle size remains stable, by making use of recognized grading indices such as the breaking parameter Br. Hence, it is reasonable to elucidate the influence of slaking against deformation properties by the representation of the grading development as the grading parameter of I_G, together with its corresponding evolution rule in particle crushing theory. This will facilitate a more comprehensive comprehension of the influence of slaking on the deformation characteristics. This study focused on examining the deformation characteristics of rocks with low strength, and then developed a strategic approach to mitigate the associated challenges. The utilization of the loading/unloading history preceding the wetting and drying cycles has led to a significant outcome in the alteration of the particle size distribution at the onset of the procedure. The implementation of this countermeasure method resulted in a decrease in the compressibility of the material during the wetting and drying cycles, reaching a level that was only half of its typical compression. In the context of constructing earthen constructions, the utilization of cyclic compaction is crucial for facilitating the fragmentation of particles. In order to reduce the amount of volumetric compression that occurs, the goal is to efficiently manage the occurrence of slaking that occurs throughout the wetting and drying cycles.

Acknowledgements

Mudstone specimens were generously provided by the University of Lampung as well as the Earthworks Research section of the Nippon Expressway Research Institute Company Limited. The authors would like to express their gratitude and appreciation to both institutions.

REFERENCES

[1] Kikumoto, M., Muir Wood, D., Russell, A, Particle Crushing and Deformation Behavior, Soils and Foundations 50, No. 4, 547-563, 2010.

[2] Yoshida, N., Enami, K., Hosokawa, K., Staged compression-immersion direct shear test on compacted crushed mudstone, Journal of Testing and Evaluation, 30(3), 239-244, 2002.

[3] Kikumoto, M., Putra, A.D., Fukuda, T, Slaking and Deformation Behavior, Geotechnique, 66, No 9, 771-785, 2016.

[4] Santi, P. M., Field Methods for Characterizing Weak Rock for Engineering, Environmental & Engineering Geoscience, XII, No. 1, 1-11, 2006.

[5] Rocchi, I., Coop, M. R., The effects of weathering on the physical and mechanical properties of a granite saprolite" Géotchnique 65, No. 6, 482-493, 2015.

[6] Fouad, A., Hassan, R and Mahmood, A. Gradation Effects on Strength and Deformation Properties of High-Quality Crushed Rock Base Materials, Transportation Research Record: Journal of the Transportation Research Board, Vol. 26, Issue 4, 2021.

[7] Hasbollah, DZA., Mohamad, ET., Hezmi, M.A., Abdullah, R.A., Yunus, NZ., Mustaffar, M., Jusoh, S.N., Azmi, M.,

Ramli, M. Taib, A.M., Comparison study on the strength index of tropical shale and sandstone influenced by moisture content, IOP Conference Series: Materials Science and Engineering, 527, 2019.

[8] Mota, R.V., Kuchiishi A, K., Takahashi, M. M, Souza, G., Camargo, F.F., Bessa, J.S., Vasconcelos, K.L., Bernucci, L., Effect of Binder Rheology and Aggregate Gradation on the Permanent Deformation of Asphalt Mixtures, International Journal of Civil Engineering, 19, 777-787, 2021.

[9] Ruarri J. D., Flemings, P. B., You, Y., Pluijm, B.A., Modification of mudstone fabric and pore structure as a result of slope failure: Ursa Basin, Gulf of Mexico, Marine Geology, Volume 341, 58-67, 2013.

[10] Sattar, A., Konagai, K., Kiyota, T., Ikeda, T., Johansson, J., Measurement of Debris Mass Changes and Assessment of the Dam-break Flood Potential of Earthquake-triggered Hattian Landslide Dam, Landslides, 8, No. 2, 171-182, 2011.

[11] Vallejo, L. E., Pappas, D., Effect of nondurable material on settlement of embankments, Transportation Research Record: Journal of the Transportation Research Board, No. 2170, 84-89, 2010.