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A. D. Putra, M. Kikumoto

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.... The properties of **mudstone** specimens **Mudstone** specimens Particle density, s Max.void ratio, emax Min.void ratio, emin Kakegawa **mudstone** 2.65 1.93 1.48 Kobe **mudstone** 2.69 1.85 1.38 ARMA 16-116 **Slaking** of **Mudstone** and **its Mechanical Consequences** in **1D compression condition** Putra1, A. D. Graduate School of Urban...

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... bedding), **1D** compres- sion, and unconfined **compressive**-strength tests. Swelling tests and thermal tests, such as thermal expansion and thermal conduc- tivity, have also been conducted, but are not reported in this pa- per. Sample depths varied from 24 to 384m. Because the geological sections from...

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Slaking of Mudstone and its Mechanical Consequences in 1D compression condition

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ABSTRACT: The slaking phenomenon of geo-materials derived from weak rocks such as mudstone or shale may cause the deformation of earth structures. Thus it should be properly considered in the process of design and construction. Previous researches indicated that slaking causes variation in particle size distribution and change in mechanical properties. However, mechanism of slaking phenomena and its mechanical consequence needs to be studied carefully. Therefore, investigation of slaking and deformation behavior through several laboratory tests was performed. In order to discuss the fundamental slaking phenomena, laboratory experiments such as ordinary acceleration slaking tests, X-Ray Fluorescence tests (XR-F) and Scanning Electron Microscopy (SEM) observation have been performed. Moreover, in order to observe the slaking phenomena and its effect on compression behavior, we modified one dimensional compression slaking test in which cyclic processes of wetting and drying is given. Kobe mudstone and Kakegawa mudstone were used to perform one-dimensional compression slaking test. The experimental results of one dimensional compression slaking tests showed that particle crushing phenomenon during the compressive stress contributes to increasing compressibility. The compressive slaking revealed that slaking under reaction stress cause the large compression even the mudstone specimens compacted to medium density. The study also suggested that it is possible to describe the slaking phenomenon in a similar way as the particle-crushing phenomenon using the scaler grading index that represents particle characteristics.

Key words:

Slaking, mudstone, particle size distribution, particle crushing, grading index

1. INTRODUCTION

Weak rocks such as mudstone or shale are highly susceptible to the weathered. Such materials have a tendency to slake and soften when immersed or contacted to the water and as a result their strength diminishes gradually with time. Due to this natural obstacle, mudstone material has been mostly disposed as waste material. However, meanwhile dealing with economic considerations and environmental concerns, several earth constructions projects propose to utilize the crushed mudstones or shales as geomaterials. Since large embankment made of these materials is considered, long term stability problem may possibly appear from the occurrence of slaking (Wakinshaw and Santi, 1996; Botts, 1998; Yoshida et.al, 2002; Santi, 2006). One of these embankments located on the Tomei expressway in Makinohara district in Japan failed during the Surugawan earthquake in 2009, with subsequent field investigation and analysis identifying the primary cause to be slaking of the mudstone (Yasuda et.al, 2012). The slaking behavior of weak rocks has been studied experimentally (Vallejo et.al 1993; Santi, 1998; Yoshida and Hosokawa, 2004) through slake-durability tests and other similar tests, in which a number of wetting and drying cycles are applied to evaluate the weathering resistance of weak rocks as shales, mudstones and siltstones. This has demonstrated that slaking cycles significantly affect the degradation process and evolution of particle size distribution in such rocks (Sadisun et.al, 2005; Gautam and Shakoor, 2013). Several studies have discussed the effects of various mineralogical, chemical, physical, and mechanical properties on the weathering characteristics of weak rocks, which have shown that rock-forming minerals have a dominant effect on the chemical weathering of sedimentary rocks (Chigira and Oyama, 1999; Bhattarai et.al, 2006; Schaefer and Birchmeir, 2013).

Table 1. The properties of mudstone specimens

Mudstone specimens	Particle density, ρ_s	Max.void ratio, e_{max}	Min.void ratio, e_{min}
Kakegawa mudstone	2.65	1.93	1.48
Kobe mudstone	2.69	1.85	1.38

Particle characteristics such as the grading of weak rock tend to evolve in response to slaking induced by wetting and drying, and this will ultimately affect the mechanical behavior as the material after slaking is quite different from the original material (Pappas and Vallejo, 1997; Vallejo and Murphy, 1999). Weak rocks may lose their strength or stiffness through slaking, as this usually results in a decrease in the particle size.

Such variation in mechanical characteristics during slaking can directly affect the deformation and failure behavior of the ground, but so far, most studies have only looked at the role of slaking in the evolution of the particle size distribution or the change in behavior of weak rocks. As there has been little discussion of the deformation behavior that is directly induced by slaking, this paper aims to address this in relation to the evolution of grading based on the stress-strain relationship that develops during slaking. Slaking and its direct effect on the deformation behavior were investigated through modified one-dimensional compression slaking test, wherein the effective stress is held constant during wetting and drying cycles in order to observe the volumetric behavior that occurs in response to slaking. In order to further explore the slaking characteristics, laboratory tests such as ordinary slake-durability tests, XRF analysis and SEM observation have also been performed.

2. MUDSTONE SPECIMENS

The mudstone specimens in this study were originated from two places in Japan, Kakegawa and Kobe district. Both of the specimens were obtained from highway embankments that consisted mainly of crushed mudstone. The Kakegawa mudstone was picked from an embankment on the Daiichi Tokai expressway, and originated from the Hijikata formation of the Pliocene age, Neogene period. The Kobe mudstone is a sedimentary rock found in the Kobe layer from the late Eocene to early Oligocene age, and was sampled from an embankment on the Shin-Tomei expressway. The general properties of mudstone specimens are summarized in Table 1.

3. INITIAL SLAKING INVESTIGATIONS

A three kinds of fundamental characteristics was initially investigated. First, the X-Ray fluorescence (XRF) analysis to identifies the essential elements of mudstone specimens. Second, scanning electron microscopy (SEM) observation was used to assess the physical and chemical characteristics, which are expected to have a major effect on the rate and process of slaking. Third, a kind of slake-durability test called “accelerated slaking”, in which a cyclic wetting and drying process is applied under unconfined condition.

3.1. X-Ray fluorescence analysis of mudstone

Moriwaki and Mitchell (1977) have previously investigated the effects of mineralogy, adsorbed-cation ratio, water content and consolidation-fluid electrolyte concentrations on the slaking mode, and concluded that this is strongly controlled by the clay mineralogy and concentration of exchangeable sodium ions. Based on this, they defined four common types of slaking as: dispersion slaking (Na-kaolinite), swelling slaking (Na-montmorillonite), body slaking (Ca-kaolinite and Ca-F) and surface slaking (Ca-montmorillonite).

Since mudstones contain a large amount of clay minerals, their intrinsic slaking behavior will be significantly affected by the amount and type of clay minerals in a particle; i.e., mixtures of clay minerals will lead to a combination of slaking modes (Vallejo and Murphy, 1999). In this study, non-destructive X-Ray fluorescences (XRF) was used to determine the chemical elements of each mudstone in order to discuss their effect on the slaking characteristics.

For this, each specimen was first oven-dried, and then crushed to produce individual particles 0.85 to 2.00 mm in diameter. The results obtained (Fig. 1) clearly show that each of the mudstones contains a high concentration of silicon (Si), aluminum (Al) and iron (Fe), along with moderate concentrations of potassium (K) and calcium (Ca). A chemical composition such as this is somewhat typical of mudstone (Hayashi et al., 1997), but the Kobe mudstone contains a particularly large amount of Si than Kakegawa mudstone. These mudstone specimens are therefore believed to consist mainly of quartz or silica in the crystal form SiO_2, along with aluminum oxide (Al_2O_3) and ferric oxide (Fe_2O_3).

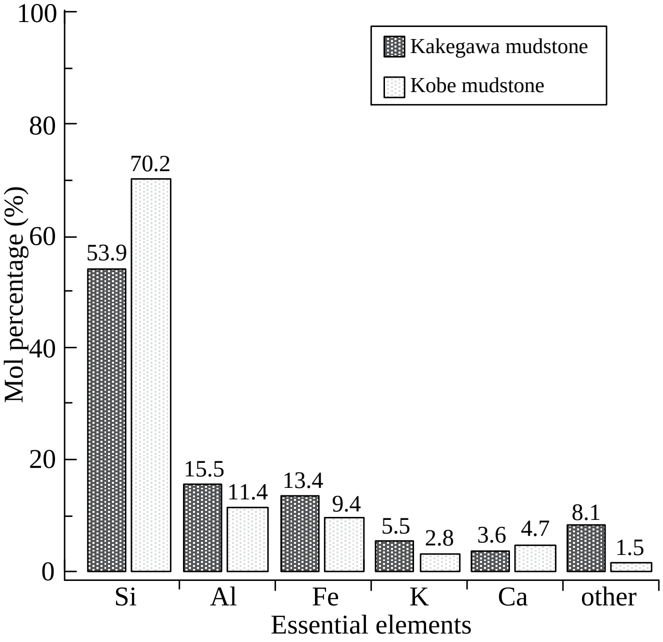


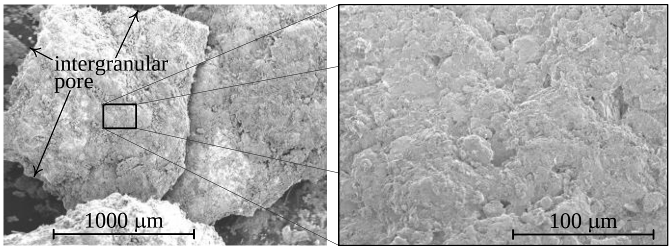
Fig. 1. Essential elements of Kakegawa and Kobe mudstone

3.2. Microscopic observation using SEM

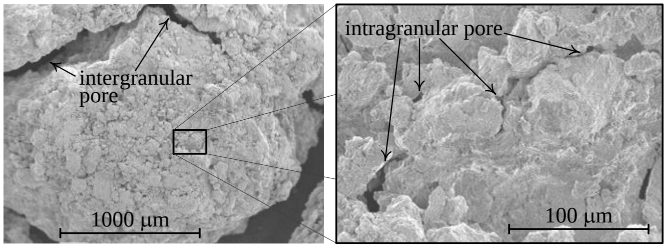
The surface characteristics of the mudstones were explored through scanning electron microscopy (SEM) using the same particle size distribution of crushed mudstone as with the XRF analysis. The low magnification images of each mudstone specimen on the left hand side in Figure 2 clearly demonstrate that each particle is in fact an aggregate of randomly shaped, clay-sized particles that produce a rough surface texture. This surface texture can be better seen in the higher magnification images on the right hand side in Figure 2. It was seen that surface texture of Kobe mudstone more particularly pronounced accumulation of tiny particles, with intra-granular pores than Kakegawa mudstone.

3.3. Accelerated Slaking Test

Applying the method described in the "accelerated rock slaking test" (JGS, 2006; East, Central and West Nippon Expressway Companies, 2012), the slake-durability of six crushed mudstone specimens was observed under unconfined (stress free) conditions. For this, mudstone particles with a diameter of 9.5 to 37.5 mm were oven-dried, and then placed in a single layer in a container. The weight of the dried specimen was measured and a picture was taken of the particles in their initial state of the mudstone specimen. In the wetting process, distilled water was poured into the container until the sample was fully submerged, and was then kept at a constant temperature of 20°C for 24 hours. In the drying process, water was ejected from the container while taking care to retain the original arrangement of particles, after which it was oven dried for 24 hours at a temperature of 90°C. A picture of each mudstone specimen was taken after each wetting and drying process, with this being repeated until a prescribed number of cycles was reached. After the last cycle, the particle size distribution of each mudstone was determined by sieving analysis, whereby the specimens were sieved in a fully dried condition using a horizontal circular movement without any tapping impulse.

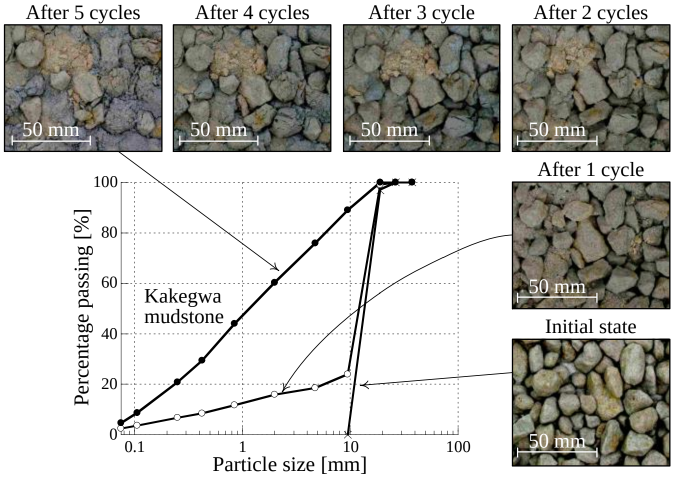


(a) Kakegawa mudstone

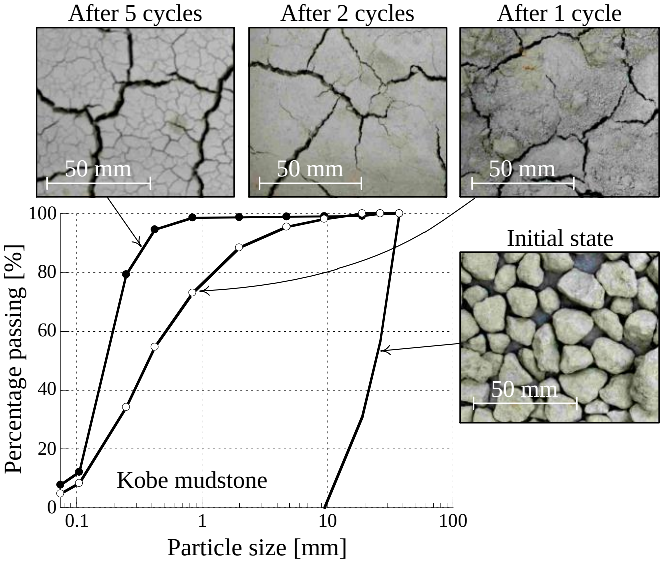


(b) Kobe mudstone

Fig. 2. Scanning Electron Microscopy (SEM) pictures showing surface textures of mudstone specimens under two different resolutions (magnification x50-500).



(a) Kakegawa mudstone



(b) Kobe mudstone

Fig. 3. Variations in the particle size distribution of two mudstone specimens during accelerated slaking test.

Figure 3 shows the result after five cycles of wetting and drying were applied to each mudstone, with a single cycle of wetting and drying also being performed with the Kakegawa and Kobe mudstones following the observation of a significant change in particle size distribution after five wetting and drying cycles. In order to discuss the variation in mechanical characteristics due to slaking, the maximum and minimum void ratios of each mudstone were also identified after each cycle of wetting and drying.

4. ONE DIMENSIONAL COMPRESSION SLAKING TEST

According to initial investigation, the change in grading of crushed mudstones due to cyclic process of wetting and drying was explored mainly through ordinary

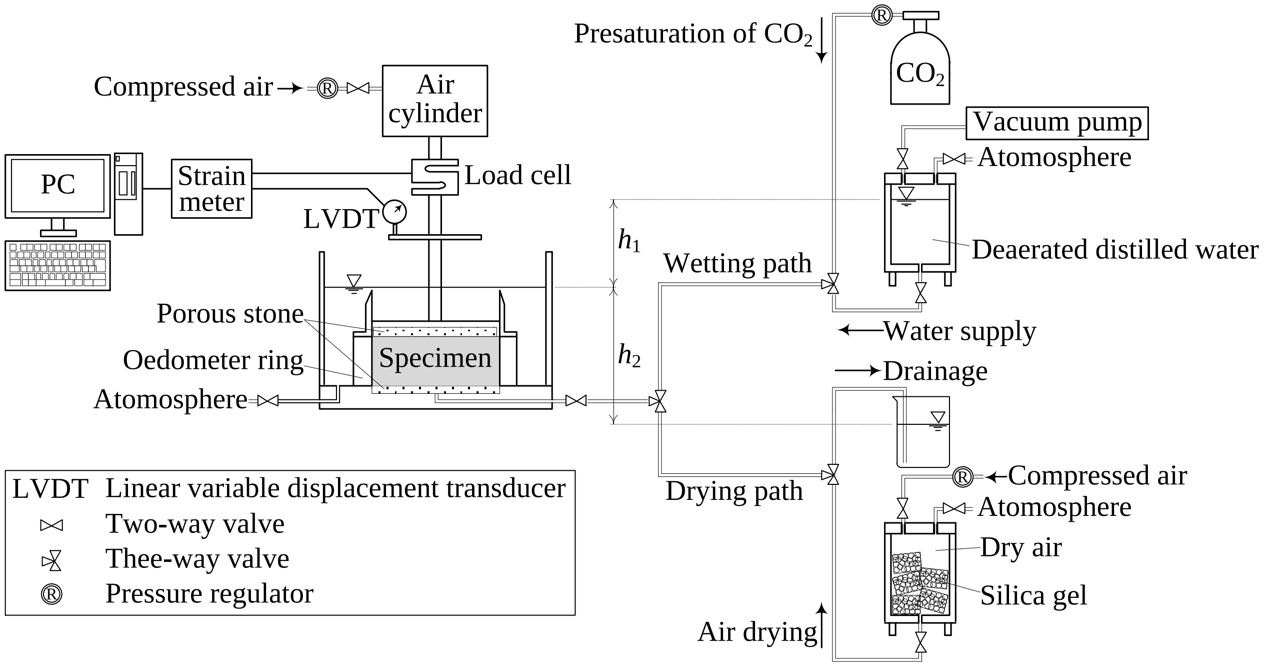


Fig. 4. A schematic framework for the one dimensional compression-slaking test.

accelerated slaking tests, and the slaking characteristics were subsequently discussed in relation to the mineralogy and surface texture of mudstones. However, whether slaking can directly affect the deformation behavior is something that also needs to be properly understood. In this chapter, slaking and its mechanical consequences are evaluated based on the results of modified one-dimensional compression slaking test that incorporates wetting and drying cycles. Slaking tests in which a cyclic process of wetting and drying was applied to mudstone specimens under one-dimensional compression were conducted in order to investigate the slaking characteristics and their influence on deformation behavior. The testing apparatus used is shown in Figure 4, and consisted of: a measuring system (left), loading system (center), and wetting and drying paths (right). For testing, dried mudstone specimens were first installed in the steel cylinder, after which the load cell and contact-type displacement gauge were installed and initialized.

The initial height of the specimen was measured to determine the initial void ratio, and then a vertical stress was applied in stages (9.8, 19.6, 39.2, 78.5, 157, 314, 628, 1256 kPa) by a pneumatic cylinder via a loading rod. The time for each loading was set to 30 minutes, as compression of the specimen immediately occurred and the volumetric behavior did not appear time dependent during the compression stage. After reaching a prescribed vertical stress, a wetting and drying cycle was carried out while keeping the vertical stress constant. The wetting process started by permeating carbon dioxide slowly through the specimen without changing the void pressure for thirty minutes to remove any air, after which distilled water was permeated through the specimen by a slight difference in water level between the water tank and specimen container h_1 until the specimen was fully submerged. After leaving the specimen submerged for 6 hours, the drying process was commenced by draining the void water from the specimen for thirty minutes through a slight difference h_2 in water level. Silica gel packs were then set around the steel cylinder of the specimen container, and dried air was slowly permeated through the specimen for 48 hours to ensure it was completely dried. This cycle of wetting and drying was repeated six times, during which time the volumetric behavior was observed. Following the final drying process, the specimen was oven-dried and then sieved using only horizontal circular movements without any tapping impulse being added.

Kakegawa and Kobe mudstone were again used for this experiment. Taking into account the results of previous testing where there is a fairly clear distinction in the extent of slaking between them. Then, according to SEM result is known that intragranular pores on the surface of the Kobe mudstone much larger than the Kakegawa.

In this test, each mudstone specimen was cylindrically shaped, with a diameter of 60 mm and a height of 40 mm. Given the size of these specimens, oven-dried particles with a diameter of 0.85 to 2.00 mm were used for testing. The specimen was prepared in two layers. Each layer was made by dropping a prescribed amount of mudstone particles from a height of around 80 mm, then by tamping with a glass bar 50 times to create a layer with the desired packing density.

As known that soaking dried specimens or unsaturated loose soils usually causes hydraulic collapse. It can happen since the variation in degree of saturation.

Therefore, medium dense specimens were generated to reduce the effect of this behavior when immersed into the water. Then, wetting and drying cycles for Kakegawa and Kobe mudstone were applied under a constant vertical effective stress σ_v' of 314 kPa and 1256 kPa. The number of cycles used was 0, 1 and 3 when σ_v' was 314 kPa, but 0 and 3 cycles were considered when σ_v' was equal to 1256 kPa.

5. RESULTS AND DISCUSSIONS

5.1. *Initial slaking investigations*

As explained, Figure 3 presents the results for the accelerated slaking test performed on the Kakegawa mudstone, which reveals that the grading was clearly altered after just the first cycle to the extent that more than 20% of the particles (by weight) were smaller than 9.5 mm. This percentage of particles smaller than 9.5 mm increased to approximately 90% after 5 cycles of wetting and drying, yet the maximum grain size remained almost same. The particle size distribution became a straight line in a semi logarithmic plot of particle size versus the percentage of finer particle by weight, and so the uniformity coefficient was apparently increased. The sequential photos presented in Figure 3 confirm that slaking occurred after each cycle of wetting and drying, with the fracture and crumbling of some particles producing finer particles, while other particles remained intact. It is apparent from the accelerated slaking test results in Figure 3 that although a change in particle size distribution occurred, the magnitude of this change in grading was notably different. The particle size distributions of the Kobe, for instance, changed quite significantly after the first wetting and drying cycle than Kakegawa mudstone, and then continued to vary with an increasing number of cycles.

There is also a clear decrease in maximum particle size with these mudstones, as most particles crumble during the first cycle and are only weakly aggregated after the drying process. Meanwhile, the sequential photos in Figure 3a and 3b all exhibit a similar slaking behavior, in that particles fracture while retaining their original shape, and so gradually crumble into finer grains with an increasing number of wetting and drying cycles. The differences in slaking behavior between Kakegawa and Kobe mudstones can be attributed to their difference in relative breakage parameter B_r (Hardin, 1985), a term that was originally proposed to represent the evolution of particle size distribution in soils exhibiting particle breakage. This is defined by the ratio between the areas ABC and ABD in Figure 5, and takes a value ranging from 0 (initial state) to 1. Observation by SEM, however, provided a much clearer interpretation of the slaking rate or slake-durability of the mudstones.

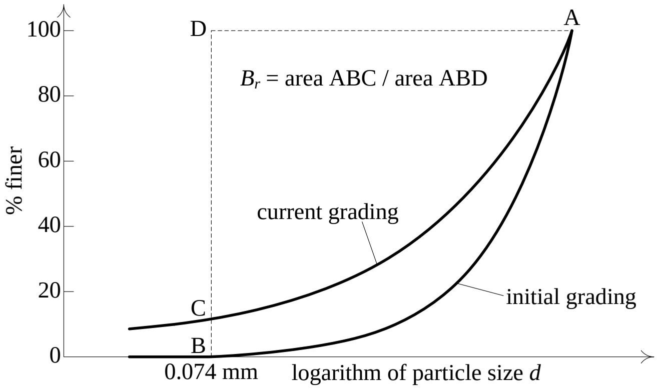
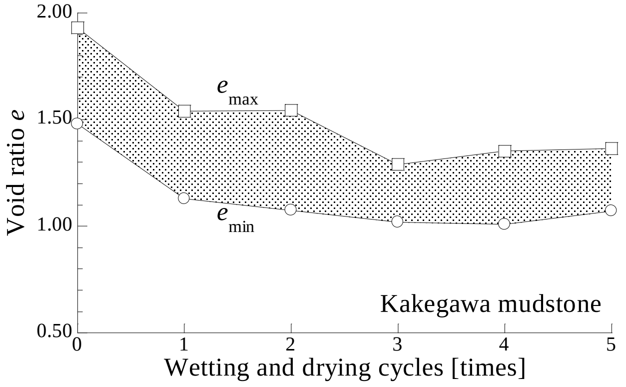
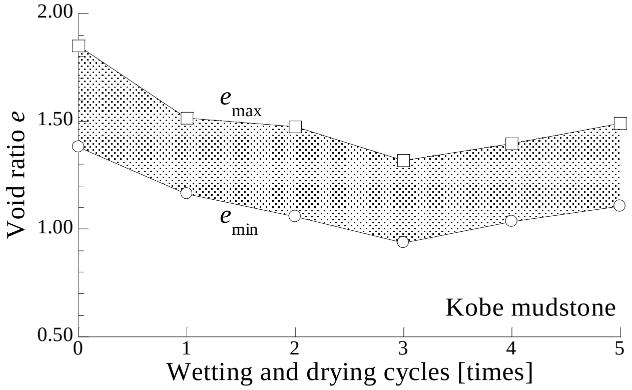


Fig. 5. Definition of Hardin's breakage parameter B_r

The particles of Kobe mudstone, for example, were easily slaked and turned into finer grains after the first cycle of wetting and drying, resulting in the intra-granular pores seen in Figure 3b (Vallejo and Murphy, 1999). The effect that changes in grading due to slaking have on the mechanical characteristics were investigated by monitoring the maximum and minimum void ratios of the Kobe and Kakegawa mudstones after each cycle of wetting and drying. As seen in Figure 6, both the maximum and minimum void ratios decrease by almost the same amount until the third cycle. In the Kakegawa mudstone, these ratios remain almost the same, while in the Kobe mudstone they slightly increase.



(a) Kakegawa mudstone



(b) Kobe mudstone

Fig. 6. Relationship between cycles of wetting and drying and maximum and minimum void ratio according to accelerated slaking test

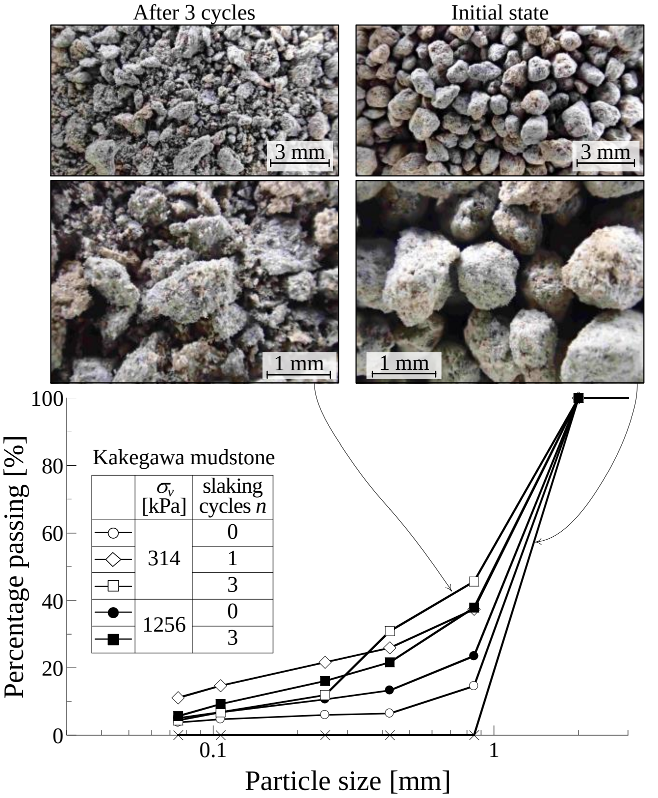
These results indicate that particle refinement occurs due to slaking, and that the mechanical characteristics (i.e., reference void ratio) are in turn altered by the change in grading. It would be intuitive to think that the void ratio at the critical state or loosest state (void ratio at normally consolidated state) would be altered in a similar way to the maximum and minimum void ratios. Experimental studies on artificial mixtures of soil particles of different sizes (Lade et al. 1998) investigated how the addition of finer particles affects the reference void ratio in relation to the maximum, minimum and critical state void ratio. This found that finer particles are initially able to distribute themselves within the voids of the coarser particles, meaning that the reference void ratio decrease. However, if more fine particles are added artificially, then the finer particles push apart the larger particles and the void ratio rises. It was concluded that modeling the effect of slaking would be possible in a similar way by extending the evolution law of the grading index to incorporate the effect of wetting and drying cycles.

5.2. One dimensional compression slaking results

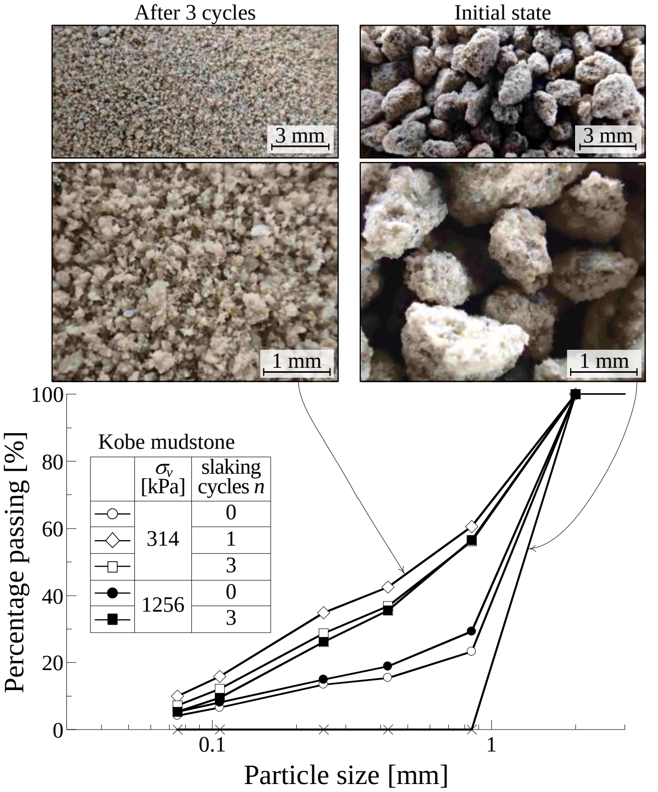
The particle size distribution in their initial state, after compression and after different numbers of wetting and drying cycles are shown in Figure 7. The test results for the Kakegawa and Kobe mudstones under a vertical effective stress $\sigma_{v'}$ of 314 and 1256 kPa are shown in Figure 7a and 7b, respectively. For each mudstone, a magnified digital photo taken of the initial state and after 3 cycles of wetting and drying under a vertical effective stress of $\sigma_{v'}$ = 314 kPa are also provided. It is evident from this that the particle size distributions of the Kakegawa and Kobe mudstones were altered after compression, and that both mudstone types experience particle breakage during one-dimensional compression.

It is also clear that there is a slightly greater change in grading at 1256 kPa, and so the evolution of grading due to particle breakage is related to an increase in the stress level. Both of mudstone specimens experienced a variation in particle size distribution after wetting and drying, but the extent of this variation differed between mudstone types. The Kakegawa and Kobe mudstone exhibited a significant change in particle size distribution, and from the enlarged photos of the particles, it is evident that this is because many particles crumbled into finer particles.

It is worth noting here that although the maximum particle size clearly decreased in the ordinary accelerated slaking tests, in which wetting and drying is applied under unconfined conditions, the maximum particle size of the three mudstone specimens remained almost constant in the one-dimensional compression slaking tests, in which a confining pressure is applied. It therefore seems reasonable to conclude that the breakage of soil particles occurs as a result of both compression and the wetting/drying cycles, with the major effect of particle breakage being to increase the proportion of fine particles that are capable of filling the voids between larger particles without noticeably changing the maximum particle size.



(a) Kakegawa mudstone



(b) Kobe mudstone

Fig. 7. Changes in the particle size properties of the two types of mudstone specimens during the one-dimensional compressive slaking testing

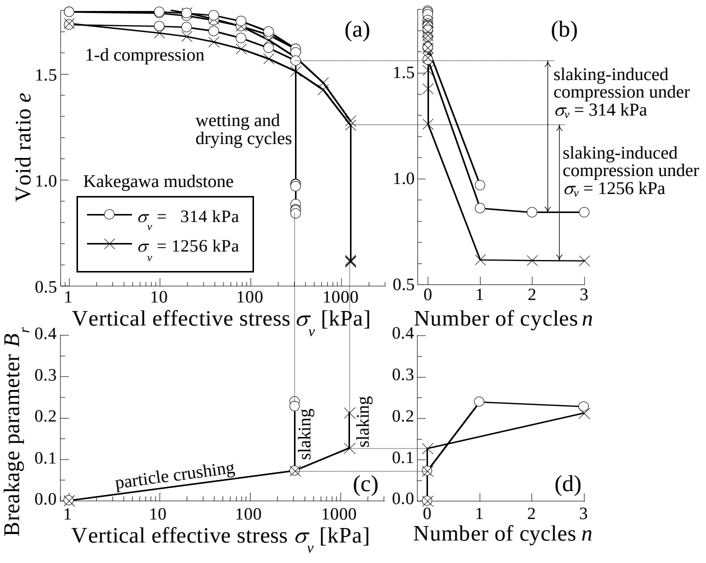


Fig. 8. Changes in the compressive properties and particle size of the Kakegawa mudstone during one-dimensional compressive slaking testing

Kikumoto et al. (2010) suggested that particle crushing due to compression or shearing does not alter the maximum particle size, and in doing so succeeded in describing the evolution of grading using a grading state index I_G defined by the ratio of areas particle size distribution curve. Note that I_G is incrementally proportional to the relative breakage B_r, which is defined as the ratio of areas ABC and ABD in Figure 5.

There is, however, considerable experimental evidence for a limit on grading before the B_r reaches 1, with the results presented here suggesting that the change in grading during wetting and drying can be described by the grading index I_G in a similar way to particle crushing. Figure 8 and 9 show the relationships between the vertical effective stress $\sigma_{v'}$, number of wetting and drying cycles n, void ratio e and breakage parameter B_r for Kakegawa and Kobe, respectively. The upper figures (a) and (b) illustrate the behavior in compression, while the lower figures (c) and (d) show the variation in grading. From the behavior of the Kakegawa mudstone shown in Figure 8, it is clear that the value of B_r (Figure 8c) increases to 0.07 at 314 kPa and to 0.13 at 1256 kPa, which is consistent with particle crushing. The compression line in the semi-logarithmic plot of e and log $\sigma_{v'}$ also becomes steeper, which further confirms of 314 that particle crushing occurred (McDowell et al., 1996; Miura and O-Hara, 1979). After the wetting and drying, the B_r value increased from 0.21 to 0.24 (Figure 8c) and the specimen experienced significant compression, to the extent that the decrease in void ratio was greater than 0.6. For the Kobe mudstone, the results for which are summarized in Figure 9, the increase in B_r during wetting and drying and the decrease in void ratio e (volumetric compression) were more significant.

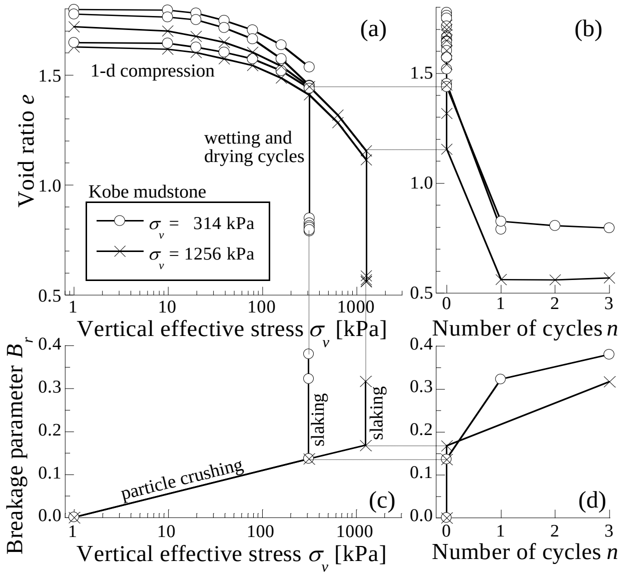


Fig. 9. Changes in the compressive properties and particle size of the Kobe mudstone during one-dimensional compressive slaking testing

It can be concluded from this that slaking induced by cyclic wetting and drying under a constant vertical effective stress causes substantial compression of mudstone.

6. CONCLUSIONS

This paper introduces the one of slaking test methods and called as modified one dimensional compression slaking test. Series of accelerated slaking tests and other laboratory analyses were conducted in conjunction with SEM observation and XRF analysis to study the slaking of mudstones and its influence on their deformation behavior. According to this research, it has been shown that different mudstone types have very different slaking characteristics, as these are affected by the existence of intra-granular pores within particles. The transformation of particle size distribution due to slaking therefore causes irreversible change in the mechanical properties of mudstone due to variation in the packing density. Moreover, the transformation of particle size distribution during compression can increase the compressibility of mudstone, with wetting and drying cycles causing significant compression despite the effective stress remaining constant. Since the transformation of particle size distribution under confined stress occurs without change in the maximum particle size, it can be described by existing indices of grading such as the grading state index I_G or breakage parameter B_r. It therefore seems reasonable to describe the effect of slaking on the deformation characteristic by representing the transformation of grading as the grading index and its evolution law, and by linking reference densities such as the maximum/minimum void ratio or critical state void ratio to the grading state index.

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REFERENCES

1. Bhattarai, P., H. Marui, B. Tiwari, N. Watanabe, G.R. Tuladhar, and Aoyama, K. 2006. Influence of weathering on physical and mechanical properties of mudstone. In *Disaster Mitigation of Debris Flows, Slope Failures and Landslides*. 2: 467-479.
2. Botts, M. E. 1998. Effects of slaking on the strength of clay shales: A critical state approach. In *Proceedings of the 2nd International Symposium on the Geotechnics of Hard Soils/Soft Rocks, Volume 1, Naples, Italy, October* 1998, 447-458.
3. Chigira, M and Oyama, T. 1999. Mechanism and effect of chemical weathering of sedimentary rocks. *Engineering Geology*. 55: 3-14.
4. East, Central and West Nippon Expressway Companies. 2012. Accelerated rock slaking test (NEXCO 110-2012). In *NEXCO testing method, Series 1: Testing method on soils*. 42-45 (in Japanese).
5. Gautam, T and Shakoor, A. 2013. Slaking behavior of clay-bearing rocks during a one-year exposure to natural climatic conditions. *Engineering Geology*, 166: 17-25.
6. Hardin, B. O. 1985. Crushing of soil particles, *Journal of Geotechnical Engineering*, 111(10): 1177-1192.
7. Hayashi K., H. Fujisawa, H. D. Holland, and H. Ohmoto. 1997. Geochemistry of 1.9 Ga sedimentary rocks from northeastern Labrador, Canada. *Journal of Geochimica et Cosmochimica Acta*. 61: 4115–4137
8. Japanese Geotechnical Society. 2006. *Method for accelerated rock slaking test* (JGS 2125-2006).
9. Kikumoto, M., Muir Wood, D. and Russell, A. 2010. Particle crushing and deformation behavior. *Soils and Foundations. Japanese Geotechnical Society*. 50(4): 547-563C.
10. Lade, P. V., Liggio, C. D., Jr., and Yamamuro, J. A., 1998. *Effects* of non-plastic fines on minimum and maximum void ratios of sand. *Geotechical Testing Journal*. 21(4): 336-347.
11. McDowell, G. R., M. D. Bolton and D. Robertson. 1996. The fractal crushing of granular materials. In *Journal* of *the Mechanics and Physics of Solids*. 44 (12): 2079–2102.
12. Miura, N. and O-Hara, S. 1979. Particle crushing of a decomposed granite soil under shear stress. Soils and Foundations. 19(3): 2-14.
13. Moriwaki, Y. and J. K. Mitchell. 1977. The role of dispersion in the slaking of intact clay. In Dispersive Clays, Related Piping and Erosion in Geotechnical Projects. *American Society for Testing and Materials ASTM STP 623*, Eds. Sherard, J. L. and Decker, R. S. 287-302.
14. Pappas, D. M. and Vallejo, L. E. 1997. The settlement and degradation on nondurable shales associated with coal mine waste embankments. *International Journal Rock Mechanics and Mineral Sciences*. 34(3-4): paper no 241.
15. Sadisun, I. A., Shimada, H., Ichinose, M. and Matsui, K. 2005. Study on the physical disintegration characteristics of Subang claystone subjected to a modified slaking index test. *Geotechnical and Geological Engineering*, 23(3): 199-218.
16. Santi, P. M. 1998. Improving the jar slake, slake index and slake durability tests for shales. In *Environmental and Engineering Geoscience*. Vol. IV. No. 3: 385-396.
17. Santi, P. M. 2006. Field methods for characterizing weak rock for engineering. *Environmental & Engineering Geoscience*, 12(1): 1–11.
18. Schaefer, V. R and Birchmeir, M. A. 2013. Mechanisms of strength loss during wetting and drying of Pierre shale. In *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris 2013*, 1183-1186.
19. Vallejo, L. E., Welsh, R. A. Jr., Lovell, C. W. and Robinson, M. K. 1993. The Influence of Fabric and Composition on the Durability of Applachian Shales. *Rock for Erosion Control*. ASTM STP 1177, Charles H. McElroy and David A. Lienhart, Eds., American Society for Testing and Materials, Philadelphia. 15-28.
20. Vallejo, L.E. and Murphy, A. S. 1999. Fractal Pores and the Degradation of Shales. *Fractals; Theory and Application in Engineering*. M. Deking et.al. (eds), 229-243.
21. Walkinshaw, J. L. and Santi, P. M. 1996. Shales and other degradable materials. *In Landslides: Investigation and Mitigation, Special Report 247, Transport Research Board, National Research Council, National Academy Press*, 555-576.
22. Yasuda, S., S. Yokota, H. Nakamura, and K. Inou. 2012. Reduction of static and dynamic shear strength due to the weathering of mudstones. In *Proceedings of the 15th World Conference on Earthquake Engineering, Lisboa, 2012*, 4-11.
23. Yoshida, N., Enami, K. and Hosokawa, K. 2002. Staged compression-immersion direct shear test on compacted crushed mudstone. *Journal of Testing and Evaluation*. 30(3): 239 – 244.
24. Yoshida, N. and Hosokawa, K. 2004. Compression and shear behavior of mudstone aggregates. *Journal of Geotechnical and Geoenvironmental Engineering*. *ASCE*. 130(5): 519-525.