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WEATHERING-INDUCED DEFORMATION OFGEOMATERIALS DERIVED FROM WEAKROCKS

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ABSTRACT

This paper investigates the slaking behaviour of several kinds of crushed mudstone and its mechanical consequences using a comprehensive set of experimental data obtained through accelerated slaking tests and newly developed one-dimensional compression slaking tests. These data confirm that slaking in crushed mudstone is accompanied by a variation in the particle size distribution during wetting and drying cycles, and a variation in grading results in an irreversible change in mechanical characteristics, such as the reference packing density. Significant compression is also found to occur without any change in effective confining stress. The results of XRD (X-ray diffraction) analysis and scanning electron microscopy (SEM) are also used to elucidate the effects of mineralogy and particle texture on the slaking characteristics of crushed mudstone. Finally, it is also mentioned that constitutive modelling can take slaking into consideration by describing the evolution of an appropriate grading index due to slaking, and then linking this to reference packing density.

Keywords: compressibility, SEM, XRD, particle size distribution, mudstones.

INTRODUCTION

In the last two decades, attract attention in studying of weathering of crushed weak rocks such as mudstones increased. Various fields including geology, mineralogy, soil and rock mechanics and geomorphology has been studied indeed. However, the relationship between triggering parameter of crushed weak rocks and deformation consequences is still not well understood. These crushed weak rocks disintegrate rapidly when subjected to changes in moisture content, and this non-durable behaviour, referred to as ‘‘slaking’’ [3] [12] is responsible for numerous slope stability problem on the earth embankments. The peak strength during compression and unconfined compression tests on crushed weak rocks is significantly reduced not only by soaking, but be affected by the cyclic wetting and drying as well [17]. The cyclic wetting and drying, then we called as “slaking cycles”.

The slaking behaviour of crushed weak rocks are usually evaluated by three types of slaking tests that include the jar slake test, the slake index test [20] and the slake durability test [5]. Among these methods, the slake durability test, recommended by both the American Society for Testing and Materials (ASTM) [1] and the International Society for Rock Mechanics (ISRM) [7], is the most repeatedly performed. The other similar tests, in accordance with the number slaking cycles are applied under unconfined conditions to evaluate the weathering resistance of granulated shale, mudstones and siltstones. This has demonstrated that slaking cycles significantly affect the degradation process and evolution of particle size distribution in such weak rocks [6] [14].

Instead of slaking cycles, the effects of various mineralogical and physical properties on the weathering of crushed weak rocks were suspected as important parameter effect on the weathering of crushed weak rocks [4]; compression of the pore air entrapped in the macro pores within the rock particles has a significant effect on the mechanism of slaking [19] and the dissolution of the cementing agents into pore water is also considered to be a cause of slaking [18]. Changes in particle size gradation of crushed weak rock tend to evolve in response to slaking induced by slaking cycles, and this will ultimately affect the mechanical behaviour, as the material after slaking is quite different from the original material. Crushed weak rocks may lose their strength during slaking cycle period, as this usually results in increase amount of small finest particle. Changes in mechanical characteristics caused by the effect of slaking cycles on the crushed weak rocks is one of the mechanical consequences that should be considered.

Figure-1. Tomei expressway fault after Surugawan earthquake in 2009(http://mtokyoblog.blogspot.jp/2009_08_01_archive.html).

Since there has still little discussion of the mechanical consequences in accordance with slaking cycles on the crushed weak rocks, the current paper aims to address this in relation to the evolution of grading based

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on the stress–strain relationship that develops during slaking. Slaking and its direct effect on the deformation behaviour were investigated through a newly developed one-dimensional compression slaking test, wherein the effective stress is held constant during wetting and drying cycles in order to observe the volumetric behaviour that occurs in response to slaking. In order to further explore the slaking characteristics, laboratory tests such as ordinary slake-durability tests, X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM) observation have also been performed.

WEATHERING OF CRUSHED WEAK ROCKS UNDER UNCONFINED STRESS CONDITION

The fundamental weathering behaviour of geo-materials derived from several mudstones was initially investigated through a kind of slake-durability test called ‘accelerated slaking’, in which a cyclic wetting and drying process is applied under unconfined conditions. XRD analysis and SEM observation were used to assess the chemical and physical characteristics.

Crushed mudstone specimen

Tests were conducted on four kinds of mudstone specimen originating from different embankments in Japan are Kakegawa, Kobe, Takasaki and Akita districts. All of these specimens were obtained from highway embankments that consisted mainly of crushed mudstone. The Kakegawa mudstone was picked from an embankment located between the Kikugawa interchange and Fukuroi interchange on the Daiichi Tokai (Tomei) 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 Takasaki mudstone was taken from an embankment located between the Fujioka interchange and Yoshii interchange on the Joetsu expressway, and which originated from the Yoshii layer of the Miocene age, Neogene period. The Akita mudstone is a sedimentary rock of the Pliocene age, Neogene period to early Pleistocene age, Quaternary period, and was taken from the Tentokuji formation near the Nihonkai-Tohoku expressway. The general properties of each mudstone are summarized in Table-1.

Table-1. Descriptions of mudstone specimens used for accelerated slaking tests.

Mudstone	Particle density, ρ_s	e_{max}	e_{min}	Geological period
Kakegawa	2.65	1.93	1.48	Neogene
Kobe	2.69	1.85	1.38	Paleogene
Takasaki	2.73	2.14	1.73	Neogene
Akita	2.77	2.40	1.86	Neogene

Constituent elements and mineralogy of mudstone

Moriwaki [12] has previously proposed that weak rocks are strongly controlled by the clay mineralogy and concentration of exchangeable sodium ions. Since mudstones contain a large amount of clay minerals, their intrinsic slaking behaviour will be significantly influenced by the amount and type of clay minerals in a particle. X-ray diffraction (XRD) was attempted in order to identify the composition of the clay and mineralogy of the crushed mudstone samples.

The samples were ground into fine particles and were then analysed by the XRD. The obtained X-ray powder pattern were compared with standard patterns to detect the types and quantities of materials. The results shown in Figure-2 indicate that the predominant minerals in the four mudstones are quartz and pyrite. The samples also contain kaolinite, feldspar and dolomite.

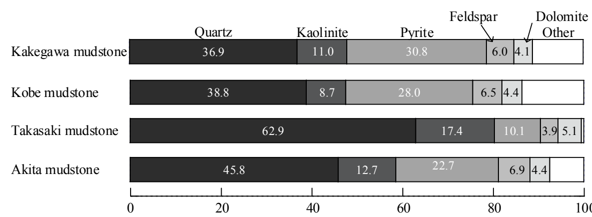

Figure-2. Mineralogy of four kinds of mudstones (X-Ray diffraction analysis, XRD).

Microscopic feature of mudstone specimens: sem observations

Several different mechanisms of the slaking of weak rocks have been pointed out in the past studies. One of the slaking mechanisms is attributed to the compression of air entrapped in the intra-granular pores of the particles [12] [19] studied the effect of the geometry of the intra-granular pores and revealed that the size of the pores and the roughness of the pore boundaries have dominant effects on the resistance of particles against slaking. The surface characteristics of the granulated mudstones were explored through SEM. The low-magnification images of each specimen on the left-hand side in Figure-3 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-3. Note that with the particles of the Kobe mudstone there is a particularly pronounced accumulation of tiny particles, with apparent intra-granular pores appearing to form within each bulk particle. In comparison, the surface texture of the Takasaki and Akita mudstone looks relatively smoother (Figure-3). In order to more understanding of intragranular existences on the mudstone particle, Hattian Bala mudstone is the good material to compare. According to SEM observation, it is difficult to see clearly the intragranular existence compare to other material. Except for Takasaki mudstone which has similarity appearance like Hattian Bala mudstone.

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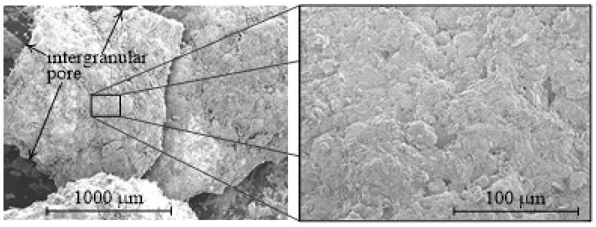
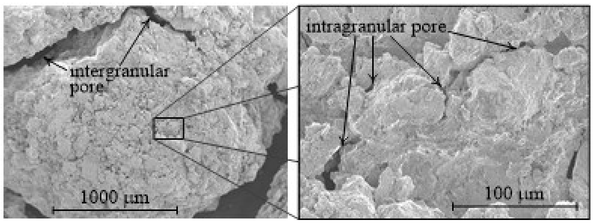
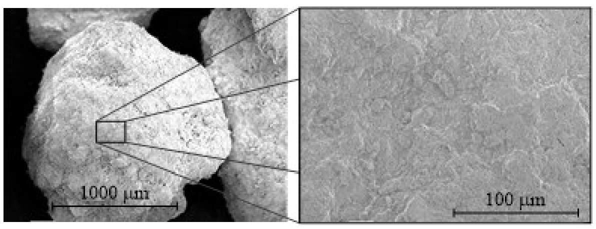


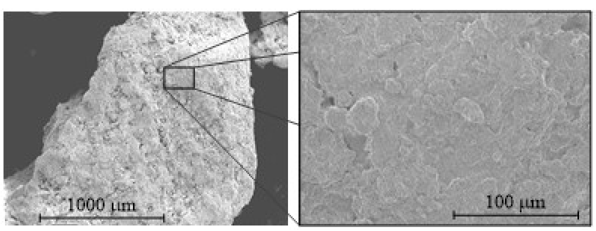
(a) Kakegawa Mudstone



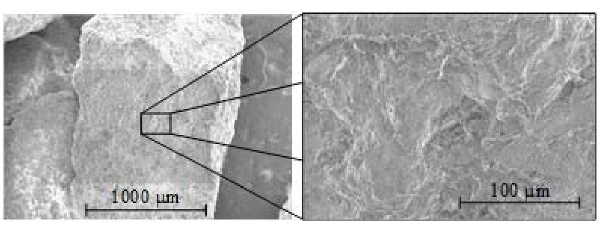
(b) Kobe Mudstone



(c) Takasaki Mudstone



(d) Akita Mudstone

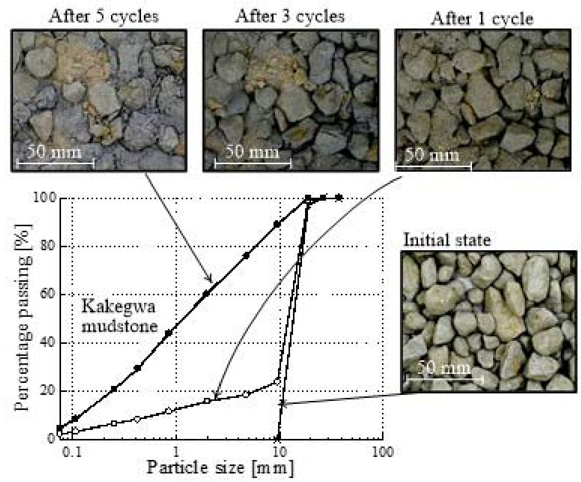


(e) Hattian Bala mudstone

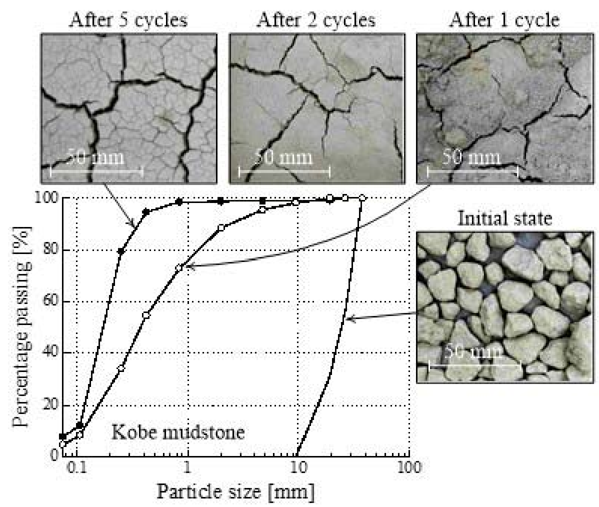
Figure-3. SEM pictures showing surface textures of mudstone specimens under two different resolutions (magnification x50-500).

Conventional slaking tests under unconfined stress condition

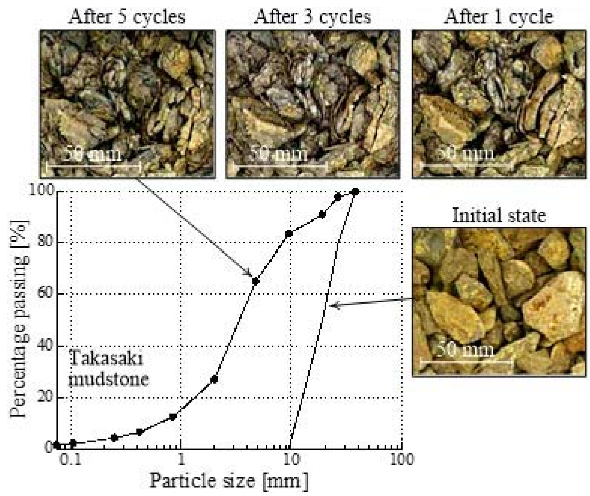
The 'accelerated rock slaking test' [13] was applied on four crushed mudstone specimens and observed under unconfined conditions. The crushed mudstones particle has diameter between of 9.5 to 37.5 mm were oven-dried, and then arranged in a single layer into a container. The weight of the specimen was measured and a picture was taken in their initial state condition. In the wetting process, distilled water was poured into the container until the sample was fully submerged, and the sample was then kept at a constant temperature of 20 °C for 24 h.



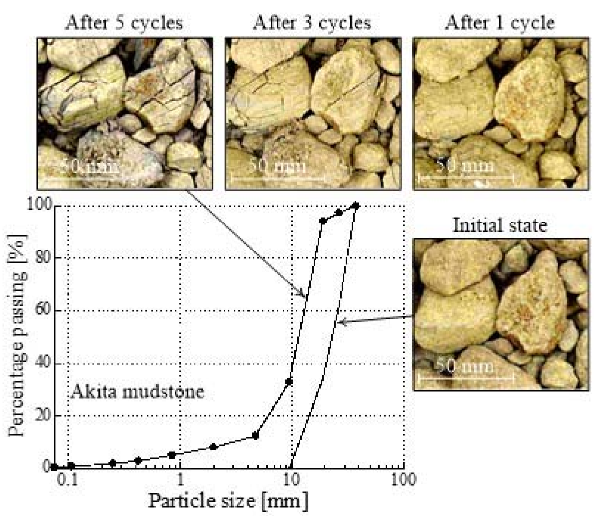
(a) Kakegawa mudstone



(b) Kobe mudstone



(c) Takasaki mudstone



(d) Akita mudstone

Figure-4. Variation in the particle size distribution of mudstones specimen during accelerated slaking test.

In the drying process, water was ejected from the container while taking care to retain the original arrangement of particles, after which the specimen was oven-dried for 24 h at a temperature of 90°C.A picture of each 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 specimen was determined by sieving analysis [8], whereby the specimens were sieved in a fully dried condition using a horizontal circular movement without any tapping impulse. Five cycles of wetting and drying were applied to each of the four mudstone types and significant change in particle size distribution after five wetting and drying cycles were observed. In order to discuss the variation in mechanical characteristics due to slaking, the maximum and minimum void ratios of the crushed Kakegawa, Kobe, Takasaki and Akita mudstone were also identified. Figure-4(a) presents the results for the accelerated slaking test performed on the crushed 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 five cycles of wetting and drying.

The particle size distribution became a straight line in a semi-logarithmic plot of particle size against the percentage of finer particle by weight, and so the uniformity coefficient was apparently increased. The sequential photographs presented in Figure-4 confirm that slaking occurred after each cycle of wetting and drying, with the fracture and crushing of some particles producing finer particles, while other particles remained intact.

It is apparent from the accelerated slaking test results for the other three specimens in Figure-4(b) to (d) that, although a change in particle size distribution occurred with all mudstone types, the magnitude of this change in grading was notably different. The particle size distributions of the crushed Kobe mudstone, for instance, changed quite significantly after the first wetting and drying cycle, and then continued to vary with an increasing number of cycles. There is also a clear decrease in maximum particle size with these specimens, as most particles crumble during the first cycle and are only weakly aggregated after the drying process. Meanwhile, the sequential photographs in Figure-4(a) to (d) of the crushed Kekagawa, Kobe, Takasaki and Akita mudstone all exhibit a similar slaking behaviour, 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. Fracture appeared to occur in a specific direction in the particles of the Takasaki mudstone, causing these to be crushed into thin layers. Meanwhile, the surface of the particles in the Akita mudstone became exfoliated like an eggshell.

WEATHERING OF CRUSHED WEAK ROCKS UNDER CONSTANT CONFINING STRESS

In the previous section, the change in grading of crushed mudstones due to the cyclic process of wetting and drying was explored mainly through ordinary accelerated slaking tests, and the slaking characteristics were subsequently discussed in relation to the mineralogy and surface texture of the particles of the crushed mudstones. However, whether slaking can directly affect the deformation behaviour is something that also needs to be properly understood. In this section, slaking and its mechanical consequences are evaluated based on the results of a newly developed, 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 remolded mudstone specimens under one-dimensional compression were conducted in order to investigate the slaking characteristics and their influence on deformation behaviour. The testing apparatus used is shown in Figure-5, and consisted of: a measuring system (left), loading system (centre), and wetting and drying paths (right). The

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specimen container was a rigid steel cylinder measuring 60 mm in diameter and 40 mm high, with porous stones installed on the top and bottom loading plates, respectively.

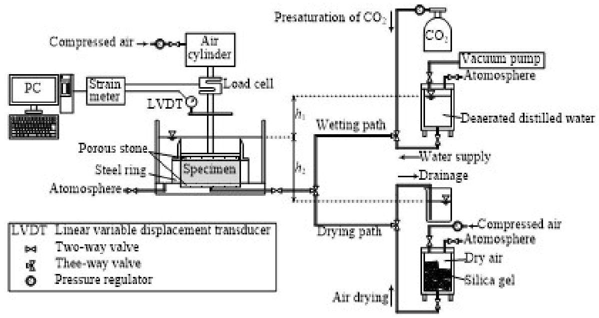

Figure-5. An overview of the set-up for the one dimensional compression-slaking test.

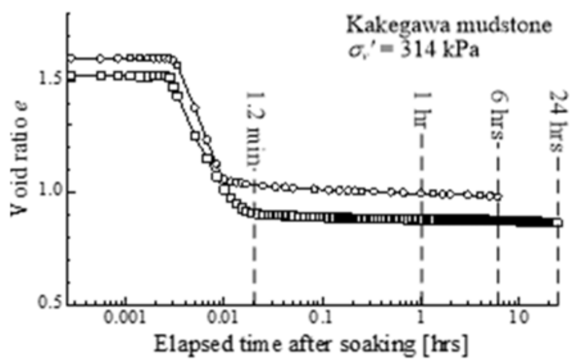

Figure-6. Variation of void ratio of crushed Kakegawa mudstone after the onset of the first wetting under 1-d compression condition (σ_v' = 314 kPa).

The vertical load was controlled by a pneumatic cylinder and measured by a load cell, with the vertical displacement then being measured by a displacement gauge. The porous stone installed on the bottom plate was connected to the inlet of the wetting and drying path. The wetting path was connected to a supply of carbon dioxide and deaerated, distilled water. The tank used for the distilled water was connected to a vacuum pump for deaeration, but was opened to the atmosphere when sending water to the specimen. The drying path consisted of a drainage path that was opened to atmospheric pressure, and an input path connected to a tank filled with compressed air dried by silica gel.

For testing, dried 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 by way of a loading rod. The time for each loading was set to 30 min, as compression of the specimen immediately occurred and the volumetric behaviour 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 30 min 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 h, the drying process was commenced by draining the void water from the specimen for 30 min 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 h to ensure it was completely dried. This cycle of wetting and drying was repeated six times, during which time the volumetric behaviour 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.

Tests were conducted on crushed Kakegawa, Kobe and Hattian Bala mudstone, the former two being selected from the four mudstone types in the previous chapter based on the clear difference in the extent of slaking between them. The Hattian Bala mudstone was sourced from a natural dam site located 3.5 km upstream of the Karli River, which is a tributary of the Jhelum River in Azad Jammu and Kashmir, Pakistan. This natural dam was formed after the 2005 Kashmir earthquake, but was subsequently breached on 9 February 2010 (4 years and 4 months later) owing to rainfall following drought [21]. The surface texture of the Hattian Bala mudstone particle can be seen in the SEM photograph provided in Figure-3(e), whereas those of Kakegawa and Kobe mudstone were provided earlier in Figure-3(a) and Figure-3(b), respectively. It is known that intra-granular pores do not occur on the surface of the Hattian Bala mudstone particle, with its surface texture being much smoother than the crushed Kakegawa and Kobe mudstones.

Each 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 tamping with a glass bar 50 times to create a layer with the desired packing density. As soaking dried or unsaturated loose soils usually cause hydraulic collapse (i.e. volumetric compression due to variation in the degree of saturation), medium-dense specimens were generated to reduce the effect of this behaviour. With the crushed Kakegawa and Kobe mudstone, wetting and drying were applied under a constant vertical effective stress, σ_v', of 314 kPa and 1256 kPa, whereas the crushed Hattian Bala mudstone was tested with a σ_v' of 314 kPa. The number of cycles used was zero, one and three when σ_v' was 314 kPa, but zero cycles and three cycles were considered when σ_v' was

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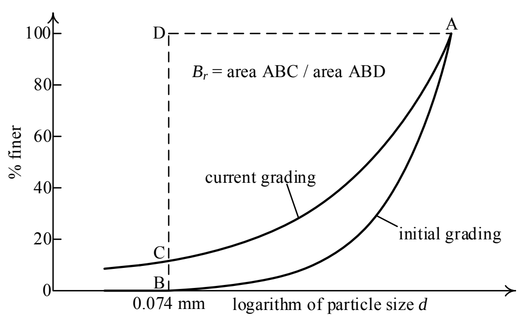
equal to 1256 kPa. Figure-6 was exhibited the variation of void ratio of Kakegawa mudstone during the first wetting cycle under a constant vertical effective stress, σ_v', of 314 kPa. It is clearly seen that void ratio immediately decrease after the first wetting cycle and it will become a little steady after 1.2 minute. Even the graphic looks flat, but actually the void ratio continued to decline in a small number. It is reveal the first statement that the number of slaking cycles is the one important parameter in reducing the peak strength of crushed weak rocks.

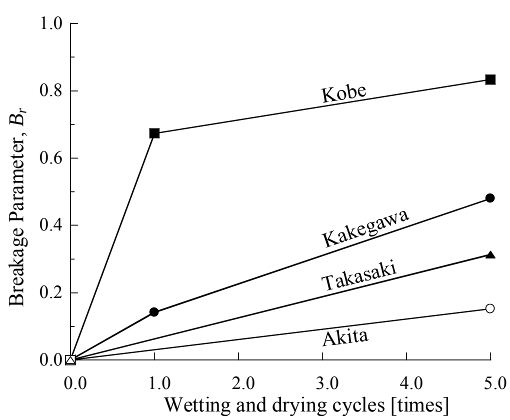
RESULTS AND DISCUSSIONS

Unconfined stress condition result

Accelerated slaking methods is one method to understanding of physical characteristics of crushed mudstones. The differences in slaking behaviour between the four mudstone specimens (not including Hattian Bala mudstone) can be investigated through their difference in relative breakage, B_r[9], a term that was originally proposed to represent the evolution of particle size distribution in soils exhibiting particle breakage.



(a) Definition of B_r parameter



(b) Variation of B_r for each specimen

Figure-7. Definition of Hardin's breakage parameter (B_r) and variation of $B_r$with cycles of wetting and drying in accelerated slaking test.

This is defined by the ratio between the areas ABC and ABD in Figure-7(a), and takes a value ranging from 0 (initial state) to 1. Figure-7(b) illustrates the variation in B_r for each of the four crushed mudstones after one and five cycles of wetting and drying. Note that the B_r of the crushed Kobe mudstone significantly increased after one cycle, and continued to increase with an increasing number of cycles. The Kakegawa mudstones also experienced a relatively large increase in B_r, whereas the increase in the B_r of the crushed Takasaki mudstone was more moderate. The crushed Akita mudstone, on the other hand, exhibited only a slight increase in B_r that was much smaller than that of the other mudstone types. The accelerated slaking test results vary greatly between the different mudstone types, and yet the increase in B_r in Figure-7(b) has no clear correlation with clay minerals in Figure-2. For instance, the crushed Kobe mudstones exhibited the greatest increase in B_r, yet contain the highest and lowest amount of silica, respectively. Expansive clay minerals (such as smectite or pyrite) are considered to be one of the major causes of the slaking as they expand due to water absorption [1] [13]. However, the results of the XRD analysis shown in Figure 2 revealed that the crushed mudstone samples used in this study do not contain such expansive clay minerals. Another possible cause of the slaking is the compression of pore air entrapped in intragranular pores when water enters the particles as a result of capillary suction [12].

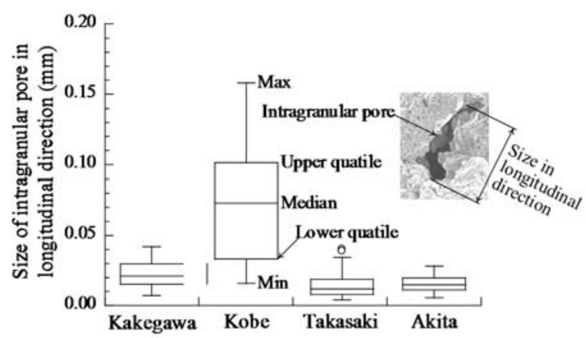


Figure-8. Size of intragranular pores within mudstone particles in longitudinal section.

Observation by SEM provided a clear interpretation of the role of the intragranular pores in the slaking rate or slake durability of the crushed mudstones. 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 intragranular pores seen in Figure-3(b). A clear correlation can be seen between the increase in B_r in Figure-7(b) and the size of the intragranular pores in the longitudinal direction presented in Figure-8. The median size of the intragranular pores of the Kobe mudstones was 0.073 mm. Meanwhile, the median size of the intragranular pores of other specimens was rather small, and ranged between 0.007 and 0.015 mm.

Vallejo *et al*. [19] investigated the slaking of shales composed of non-expansive clay minerals and reported that the slaking caused by the pore air compression was more pronounced in shales having a

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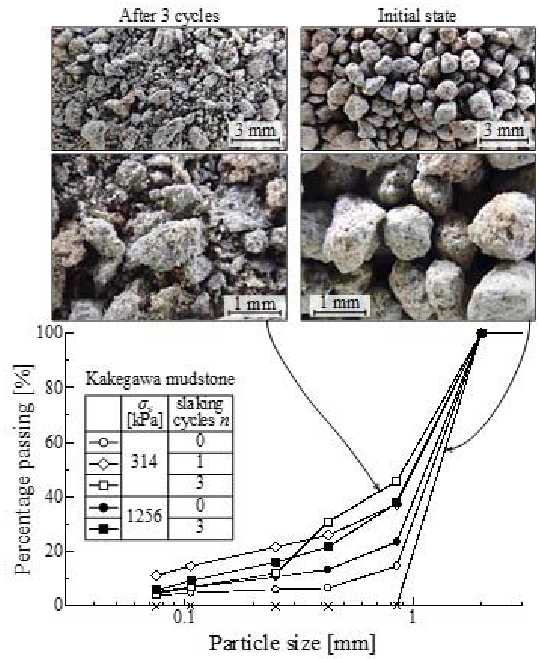
mean value of the equivalent diameter equal to or smaller than 0.060 mm. Here, the equivalent diameter is the diameter of a circle that has the same area as the intra-granular pore, and is slightly smaller than the size of the pores in the longitudinal direction. It is thus concluded that there exists an appropriate range of size of the intra-granular pores at which the particles are likely to slake.

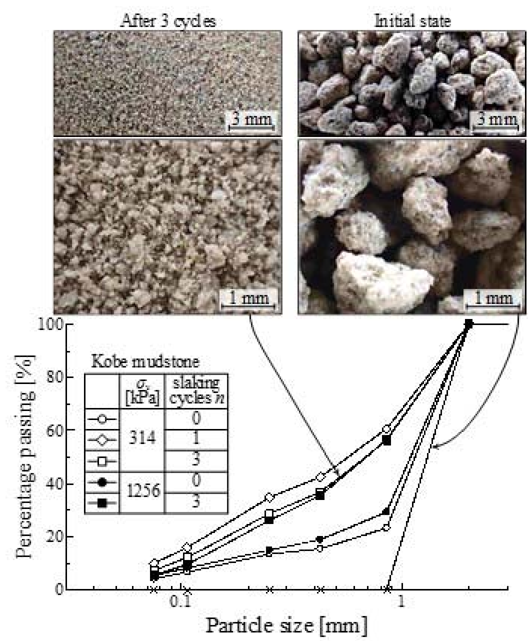
The effects that changes in grading due to slaking have on the mechanical characteristics were investigated by monitoring the maximum and minimum void ratios of the crushed Kobe, Kakegawa and Takasaki mudstones after each cycle of wetting and drying. As explained on Figure 6, the void ratio exhibited continued to decline after several minutes of first wetting cycles of slaking. The weathered on the crushed weak rocks such as mudstone easily shown according to the result. Declining of void ratio also representing of deformation behaviour as a consequences of slaking phenomenon. However, if more fine particles are added artificially, then the finer particles start to push apart the larger particles and the void ratio rises.

One-dimensional compression slaking result

The particle size distribution of the three types of crushed mudstones in their initial state, after compression and after different numbers of wetting and drying cycles, are shown in Figure-9. The test results for the crushed Kakegawa and Kobe mudstones under a vertical effective stress σ_v' of 314 and 1256 kPa are shown in Figures 9(a) and 9(b), respectively, whereas the results for the crushed Hattian Bala mudstone under a vertical effective stress σ_v' of 314 kPa are provided in Figure-9(c). For each specimen, magnified digital photographs taken of the initial state and after three cycles of wetting and drying under a vertical effective stress of σ_v'= 314 kPa are also provided. It is evident from this that the particle size distributions of the crushed Kakegawa and Kobe mudstones were altered after compression, and that both mudstone types experience particle breakage during one-dimensional compression.



(a) Kakegawa mudstone



(b) Kobe mudstone

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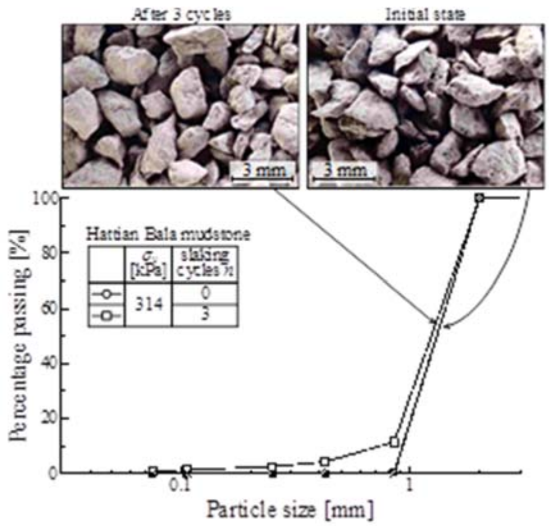

(c) Hattian Bala mudstone

Figure-9. Change in particle size of three mudstone specimen during one-dimensional compression slaking testing.

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. The crushed Hattian Bala mudstone, however, retains its original particle size distribution, and does not seem to exhibit any particle breakage under a stress of less than 314 kPa. All of the crushed mudstone specimens experienced a variation in particle size distribution after wetting and drying, but the extent of this variation differed between mudstone types. The crushed Kakegawa and Kobe mudstone exhibited a significant change in particle size distribution, and from the enlarged photographs of the particles, it is evident that this is because many particles crumbled into finer particles. In contrast, the change in grading of the crushed Hattian Bala mudstone in response to wetting and drying was relatively small, and the particles looked much the same before and after testing.

Furthermore, the particle size distribution of Hattian Bala mudstone almost did not changes during slaking cycles period. It is possible since the particles of Hattian Bala does not have any intragranular pores. The surface appearance of Hattian Bala particles on Figure-3(e) was proven this conclusion. It is worth noting here that, even 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 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 fracture and crush of mudstone 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 and causing volumetric compression without noticeably changing the maximum particle size.

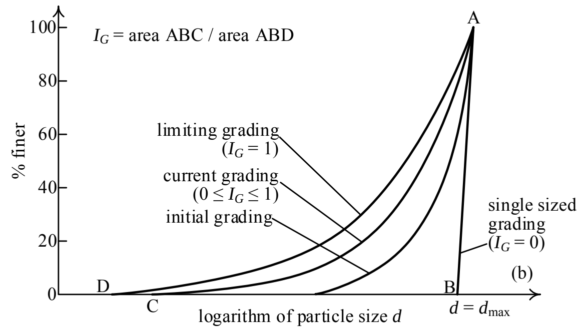

Figure-10. Schematic diagram of grading evolution and definition of a grading state index I_G based on the ratio of areas ABC and ABD.

Kikumoto [9] [10] proposed that the 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 ABC and ABD (Figure-10). 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-7(a). Although both indices take a value from 0 to 1, Hardin's breakage parameter B_r does not incorporate the idea of limiting or critical grading. 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. The grain size analysis was performed after the test on each specimen to produce the breakage parameter, B_r.

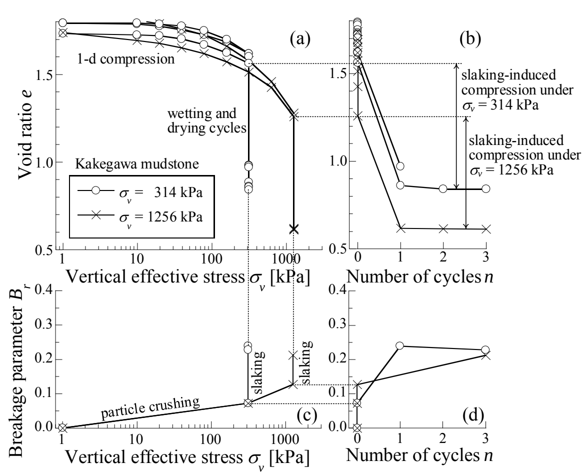

Figure-11. Change in compressive properties and particle size of Kakegawa mudstone during one-dimensional compressive slaking testing.

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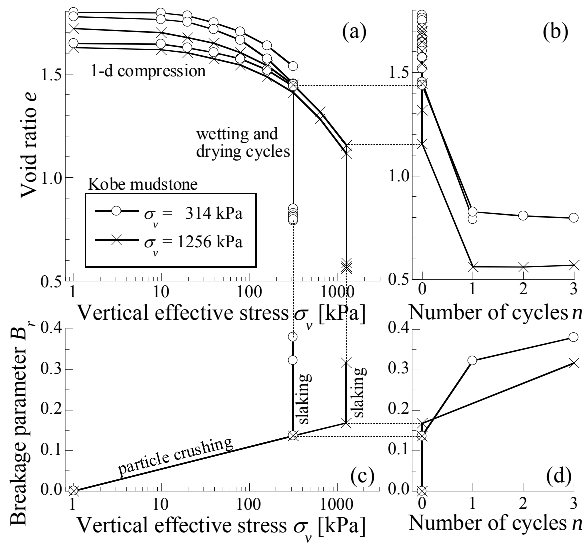

Figure-12. Change in compressive properties and particle size of Kobe mudstone during one-dimensional compressive slaking testing.

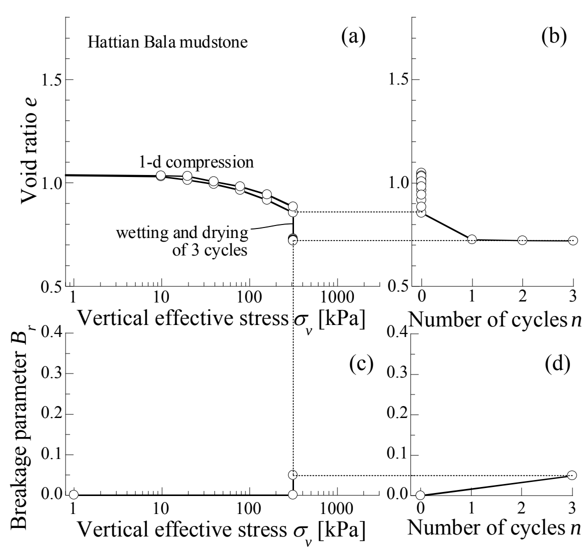

Figure-13. Change in compressive properties and particle size of Hattian Bala mudstone during one-dimensional compressive slaking testing.

It is necessary since one of the purpose of this study to generate the constitutive modelling in the future and indicate the relationships between the vertical effective stress σ_v', number of wetting and drying cycles *n*, void ratio *e* and breakage parameter B_r for the crushed Kakegawa, Kobe and Hattian Bala mudstone, respectively as exhibited on Figure-11, Figure-12 and Figure-13. The upper figures (figure parts (a) and (b)) illustrate the behaviour in compression, whereas the lower figures (figure parts (c) and (d)) show the variation in grading. From the behaviour of the crushed Kakegawa mudstone shown in Figure-11, it is clear that the value of B_r (Figure-11(c)) 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 σ_v' also becomes steeper, which further confirms that particle crushing occurred [9] [11]. After the wetting and drying, the B_r value increased from 0.21 to 0.24 (Figure-11(b)) and the specimen experienced significant compression, to the extent that the decrease in void ratio was greater than 0.6. For the crushed Kobe mudstone, the results for which are summarized in Figure-11, the increase in Br during wetting and drying and the decrease in void ratio e (volumetric compression) were more significant. In contrast, the increase in B_r of the crushed Hattian Bala mudstone was almost zero during the compression stage, and the compression line in the e–ln σ_v' plane was comparatively flat. This indicates that the variation in B_r during wetting and drying is rather small, and thus so is the volumetric compression induced by slaking. It can be concluded from this that slaking induced by cyclic wetting and drying under a constant vertical effective stress causes substantial compression of geomaterials derived from crushed weak rocks such as mudstone.

CONCLUSIONS

All experiments which had been done on this paper has a purposes to have better understanding of the mechanical consequences on the crushed weak rocks which affected by wetting and drying cycles. With a view to emphasize the conclusion of this study, several additional laboratory experiments had performed. SEM observation and XRD analysis of granular fills derived from mudstones and its influence on their deformation behaviour was observed. Through this, it has been shown that different mudstone typeshave very different slaking characteristics, as these are affected by the existence of intragranular pores within particles. The evolution of grading due to slaking therefore causes irreversible change in the mechanical properties of crushed mudstone attributable to variation in the density compaction. Moreover, the changes in particle size distribution as an evolution grading during compression can increase the compressibility of crushed mudstone, with wetting and drying cycles causing significant compression despite the effective stress remaining constant. Since the evolution 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 evolution of grading as the grading index I_G and its evolution law, and by linking reference densities such as the maximum/minimum void ratio or critical state void ratio to I_G. The variation of void ratio during slaking cycles and potential breakage on the medium dense compaction also explain that the possibility to utilize of crushed weak rocks as an earth embankment material is

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still possible with some of the provisions related to density.

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