Weathering geomaterials and deformation behavior

August 2016
Conference: IC-STAR 2016
Project: Weathering of geomateirals

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Abstract and Figures

This paper investigates the slaking behavior of several kinds of mudstone and the 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.

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***Keywords*— compressibility, particle size distribution, accelerated-slaking, microscopy, mineralogy, mudstones.**

I. INTRODUCTION

THERE is a need for greater attention to be paid to geomaterials derived from weak sedimentary soft rocks such as mudstones, siltstones, tuffs, shales and other clay-bearing rocks. Sedimentary soft rocks cannot be classified as hard rocks or soft soils in terms of their behavior, it's show an intermediate behavior. The performance of ground fills derived from such materials is closely related to the strength and durability of the individual rock fragments. Once disturbed or weathered, some of these materials retain the mechanical characteristics of the original material, but others transform within a time frame that is relevant to the long-term performance of earthen structures such as embankments and cut slopes (Botts, 1998; Santi, 2006; Vallejo & Pappas, 2010). This has already led to numerous problems being encountered in the construction of embankments or cut slopes through mudstone or shale formations (Shamburger et al., 1975; Hopkins & Beckham, 1998), as well as the several embankments in Japan that are constructed using crushed mudstone. One of these embankments, located on the Tomei expressway in Makinohara district, 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).

Landslides occurring on tertiary sedimentary rocks are also of great interest in places where such deposits are widely exposed, as the bedrock or mudstone in such cases has usually been weathered and gradually weakened into landslide clay. When subjected to repeated wetting and drying cycles, granular fills derived from mudstones and shales tend to develop a finer grain size through slaking, which also reduces the stiffness and strength of the material and can lead to structural instability. This makes it necessary to understand fully the weathering process and the changes in the physical and mechanical characteristics of geomaterials derived from weak rocks such as mudstones, especially when it comes to studying the long-term stability problems of slopes (Bhattarai et al., 2006).

The slaking of weak rocks has been extensively studied experimentally (Nakano, 1967; Franklin & Chandra, 1972; Moriwaki, 1974; Vallejo et al., 1993; Yoshida et al., 2002; Yoshida & Hosokawa, 2004; Yasuda et al., 2012) through slake-durability tests (Franklin & Chandra, 1972) and other similar tests, in which a number of wetting and drying cycles are applied under unconfined conditions to evaluate the weathering resistance of granulated 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 & Shakoor, 2013).

Meanwhile, loading tests such as one-dimensional compression and unconfined compression tests performed on weak rocks with varying degrees of slaking have revealed that peak strength is significantly reduced not only by soaking (Yoshida & Hosokawa, 2004; Schaefer & Birchmeir, 2013), but also by cyclic wetting and drying (Botts, 1998; Yasuda et al., 2012; Rocchi & Coop, 2015).

Fig. 1. Tomei expressway fault after Surugawan earthquake in 2009

Manuscript received May 20, 2016. This work was supported in part by Indonesia Endowment Fund for Education (LPDP), Ministry of Finance Republic of Indonesia provided to first author and the Earthworks Research Section of the Nippon Expressway Research Institute Company Limited for providing mudstone specimens and JSPS KAKENHI Grant Numbers 20860045, 22760355, 24360192 provided to second author.

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Several studies have discussed the effects of various mineralogical, chemical, physical and mechanical properties on the weathering characteristics of weak rocks. These studies have shown: expansive clay minerals have a dominant effect on the weathering of sedimentary rocks (Moriwaki, 1974; Chigira & Oyama, 1999; Bhattarai et al., 2006; Schaefer & Birchmeir, 2013); compression of the pore air entrapped in the macro pores within the rock particles has a significant effect on the mechanism of slaking (Moriwaki, 1974; Vallejo, et al., 1993) and the dissolution of the cementing agents into pore water is also considered to be a cause of slaking (Surendra et al., 1981). The mechanism of the pore air compression within intragranular pores was further studied and the dominant effects of the roughness of the pore boundaries and the diameter of the pores on the resistance of particles against slaking as well as crushing have been pointed out (Vallejo et al., 1993; Vallejo & Stewart Murphy, 1999).

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. 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; however, 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. Pappas & Vallejo (1997) conducted static-compression-creep tests, in which time-dependent deformation of non-durable shales due to water absorption was measured under confined conditions. However, there has still been little discussion of the deformation behavior that is directly induced by slaking. Thus, the current 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 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 behavior 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.

II. Slaking of Mudstone under Unconfined Stress Condition

The fundamental slaking behavior of geomaterials 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 (i.e. stress-free) conditions. XRD analysis and SEM observation were used to assess the chemical and physical characteristics, which are expected to have a major effect on the rate and process of slaking.

A. Crushed Mudstone Specimens

Tests were conducted on four kinds of mudstone specimen originating from different embankments in Japan, such as Kakegawa, Kobe, Takasaki and Akita districts.

TABLE I
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

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 I.

B. Constituent Elements and Mineralogy of Mudstone

Moriwaki (1974) has previously investigated the effects of mineralogy, adsorbed-cation ratio, water content and consolidation-fluid electrolyte concentration on the slaking mode, and concluded that this is strongly controlled by the clay mineralogy and concentration of exchangeable sodium ions. Based on this, he defined four common types of slaking as: dispersion slaking (sodium (Na)-kaolinite), swelling slaking (Na-montmorillonite), body slaking (calcium (Ca)-kaolinite and Ca-illite) and surface slaking (Ca montmorillonite). As 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; that is, mixtures of clay minerals will lead to a combination of slaking modes (Santi & Koncagul, 1996). X-ray diffraction 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 analyzed by the XRD. The obtained X-ray powder diffractogram were compared with standard patterns to detect the types and quantities of materials. The results shown in Fig. 2 indicate that the predominant minerals in the six mudstones are quartz and pyrite. The samples also contain kaolinite, feldspar and dolomite.

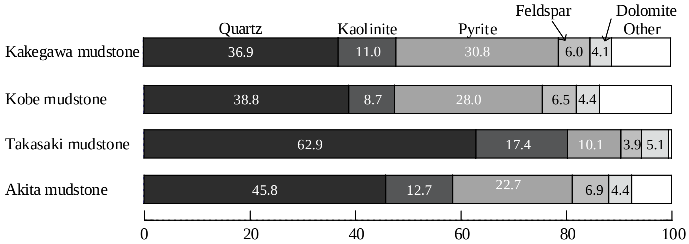
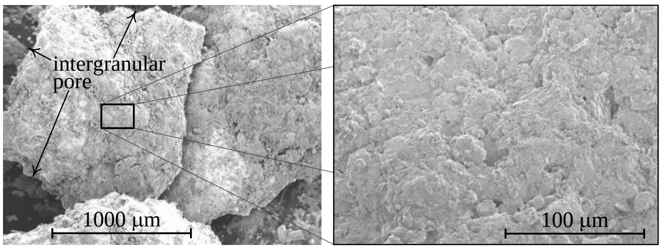


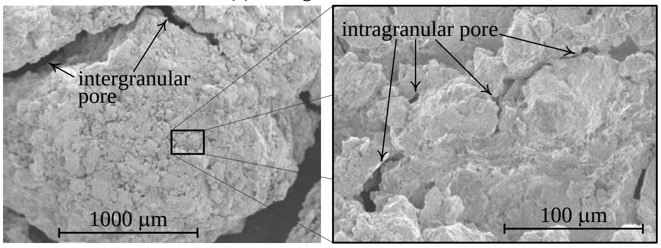
Fig. 2. Mineralogy of four kinds of mudstones (XRD analysis)

C. Microscopic Feature of Mudstone specimens: SEM observations

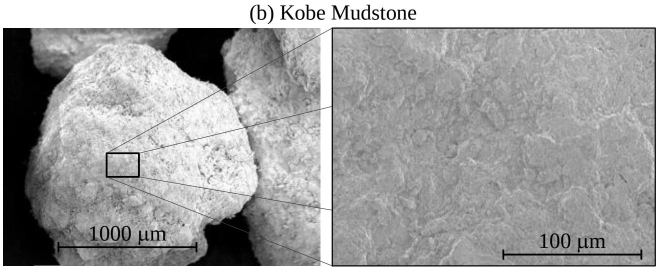
Several different mechanisms of the slaking of weak rocks have been pointed out in the past studies. One of the slaking mechanisms is attributed to the compression of air entrapped in the intragranular pores of the particles (Moriwaki, 1974). Vallejo et al. (1993) and Vallejo & Stewart-Murphy (1999) studied the effect of the geometry of the intragranular 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.



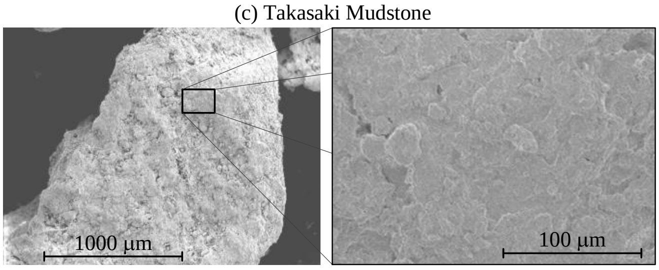
(a) Kakegawa Mudstone



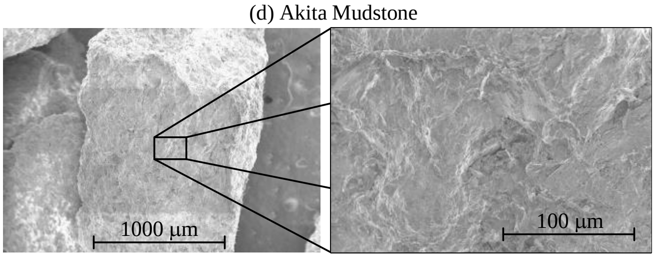
(b) Kobe Mudstone



(c) Takasaki Mudstone



(d) Akita Mudstone



(e) Hattian Bala mudstone

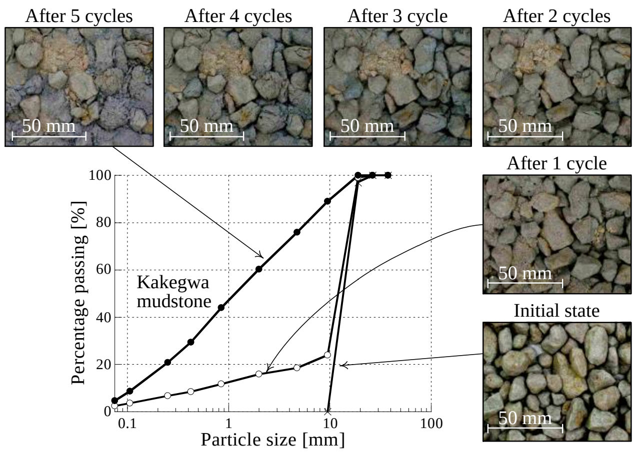
Fig. 3. SEM pictures showing surface textures of mudstone specimens under two different resolutions (magnification x50-500).

The low-magnification images of each specimen on the left-hand side in Fig. 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 Fig. 3. Note that with the particles of the Kobe mudstone there is a particularly pronounced accumulation of tiny particles, with apparent intragranular pores appearing to form within each bulk particle. In comparison, the surface texture of the Takasaki and Akita mudstone looks relatively smoother. In order to grasp the characteristic of the intragranular pores of the six specimens, the sizes of the intragranular pores were digitized using the SEM micrographs of the particles.

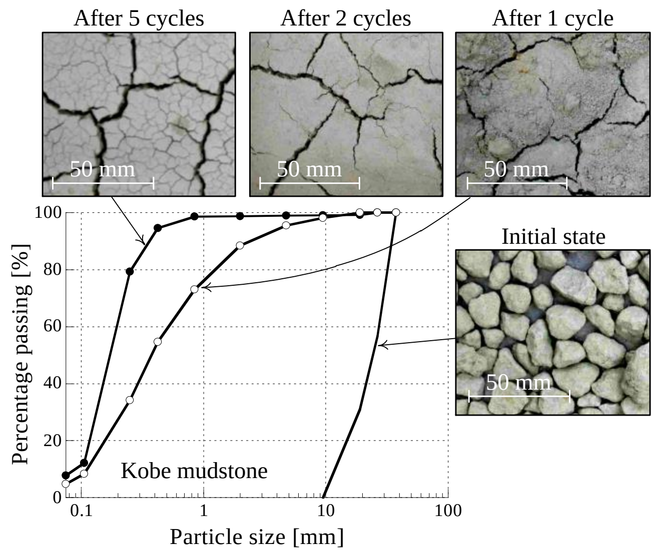
D. Conventional Slaking Tests under Unconfined Stress Condition: Accelerated Slaking test

Using the method described in the ‘accelerated rock slaking test’ (JGS, 2006; NEXCO-RI, 2012), the slake durability of four crushed mudstone specimens was observed under unconfined (stress-free) conditions. For this, crushed 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 in the specimen. 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. 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.

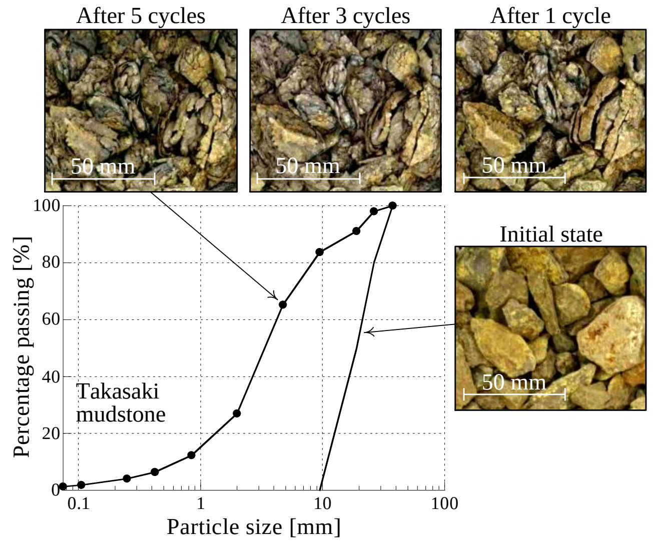
A picture of each specimen was taken after each wetting and drying process, with this being repeated until a prescribed number of cycles was reached. After the last cycle, the particle size distribution of each specimen was determined by sieving analysis (JGS, 2009), whereby the specimens were sieved 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.



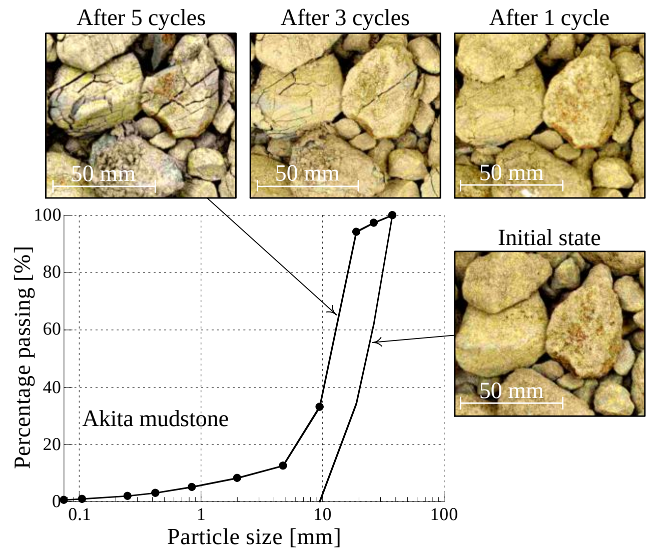
(a) Kakegawa mudstone



(b) Kobe mudstone



(c) Takasaki mudstone



(d) Akita mudstone

Fig. 4. Variation in the particle size distribution of Kakegawa mudstone during accelerated slaking test

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, yet the maximum grain size remained almost the same. 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 Fig. 4 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 for the other three specimens in Fig. 4(b) – 4(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 Figs 4(a) - 4(d) of the crushed Kekagawa, Kobe, Takasaki and Akita mudstone 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. 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.

III. Slaking under One-dimensional Compression Slaking Test

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 behavior 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 behavior. The testing apparatus used is shown in Fig. 5, and consisted of: a measuring system (left), loading system (center), and wetting and drying paths (right). The 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.

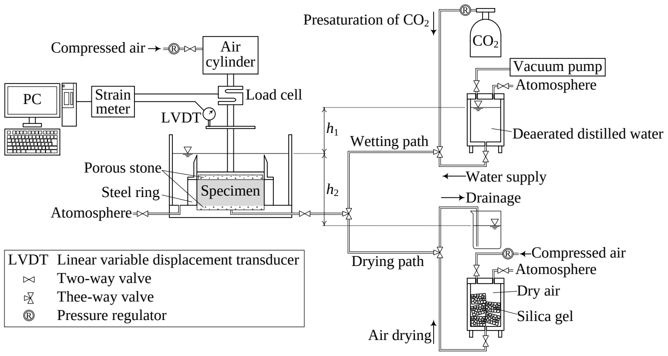


Fig. 5. An overview of the set-up for the one dimensional compression-slaking test

. 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.

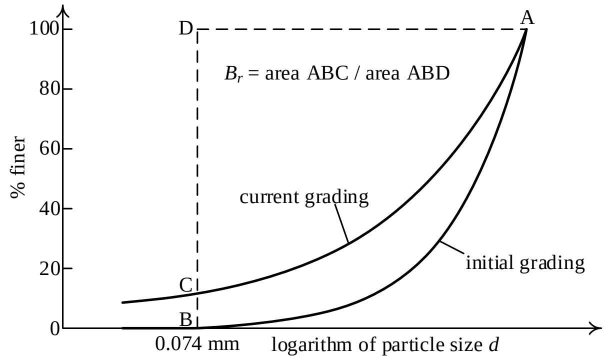
For testing, dried specimens were first installed in the steel cylinder, after which the load cell and contact-type displacement gauge were installed and initialized. The initial height of the specimen was measured to determine the initial void ratio, and then a vertical stress was applied in stages (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 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 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 h1 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 h2 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 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.

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 (Sattar et al., 2011). The surface texture of the Hattian Bala mudstone particle can be seen in the SEM photograph provided in Fig. 3(e), whereas those of Kakegawa and Kobe mudstone were provided earlier in Figs 3(a) and 3(b), respectively. It is known that intragranular 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 behavior. 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 equal to 1256 kPa.

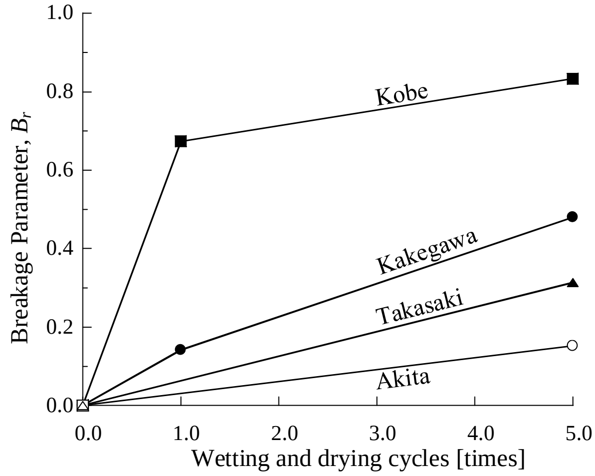
IV. RESULTS AND DISCUSSION

A. *Unconfined Stress Condition*

The differences in slaking behavior between the four mudstone specimens can be investigated through their difference in relative breakage, 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 Fig. 6(a), and takes a value ranging from 0 (initial state) to 1. Fig. 6(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 Fig. 6(b) has no clear correlation with clay minerals in Fig. 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 smectite clay minerals are considered to be one of the major causes of the slaking as they expand due to water absorption (Moriwaki, 1974; Andrews et al., 1980).



(a) Definition of Br paremeter



(b) Variation of B_r for each specimen

Fig. 6. Definition of Hardin's breakage parameter (B_r) and variation of B_r with cycles of wetting and drying in accelerated slaking test

However, the results of the XRD analysis shown in Fig. 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 (Moriwaki, 1974). 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 Fig. 3(b). A clear correlation can be seen between the increase in B_r in Fig. 6(b) and the size of the intragranular pores in the longitudinal direction presented in Fig. 7. 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. (1993) 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 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 intragranular 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 intragranular pores at which the particles are likely to slake.

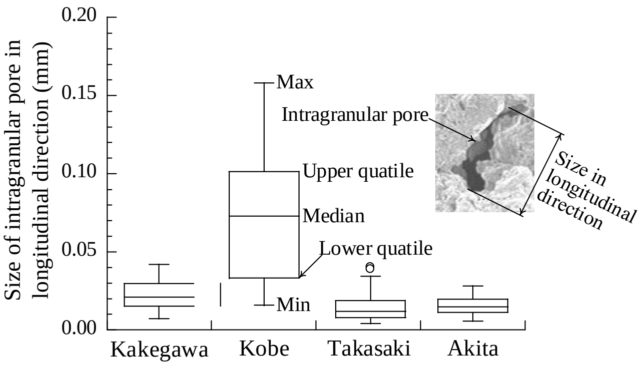
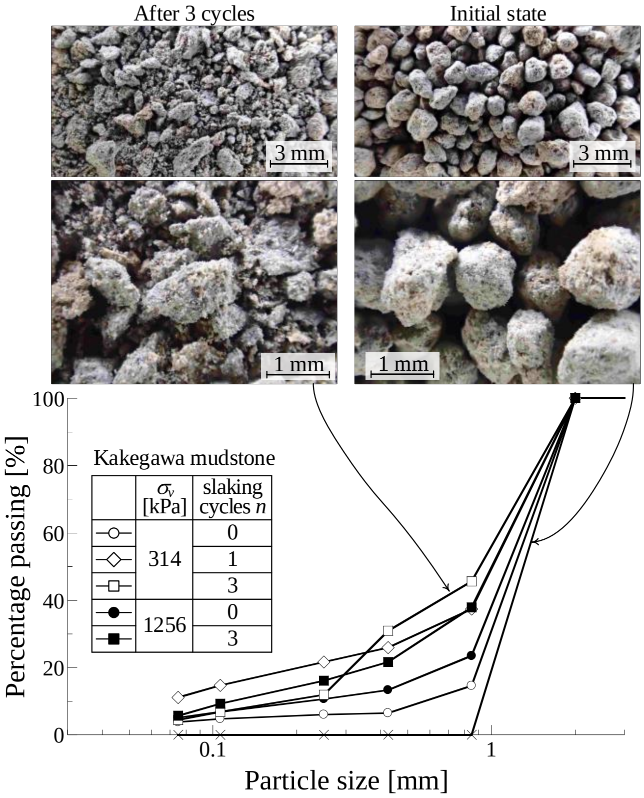


Fig. 7. Size of intragranular pores within mudstone particles in longitudinal section

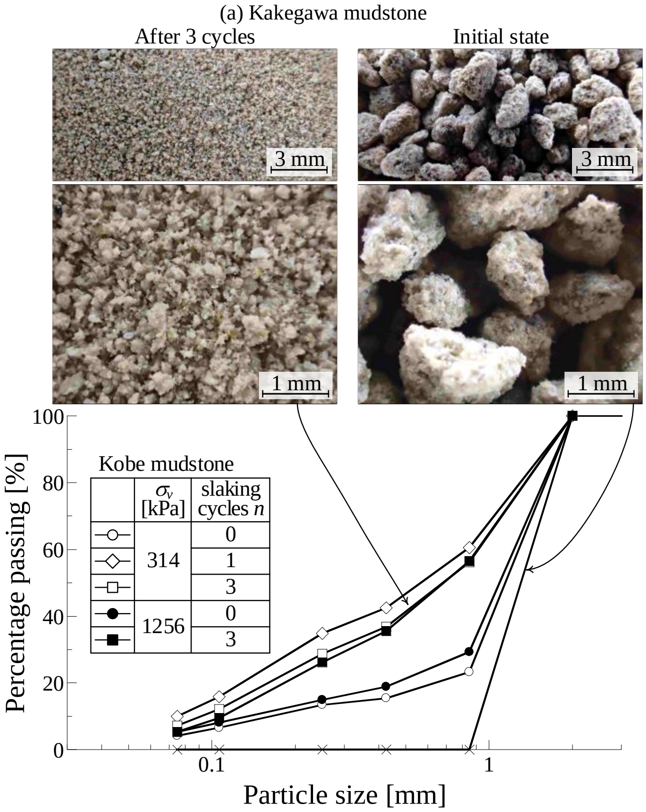
The effects that changes in grading due to slaking have on the mechanical characteristics were investigated by monitoring the maximum and minimum void ratios of the crushed Kobe, Kakegawa and Takasaki mudstones after each cycle of wetting and drying. However, if more fine particles are added artificially, then the finer particles start to push apart the larger particles and the void ratio rises. Kikumoto et al. (2010) developed a constitutive model for this, in which the effect of changing grading due to particle breakage is considered by relating a grading state index I_G to the reference void ratio. It was concluded that modelling 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.

B. One-Dimensional Compression Slaking Test

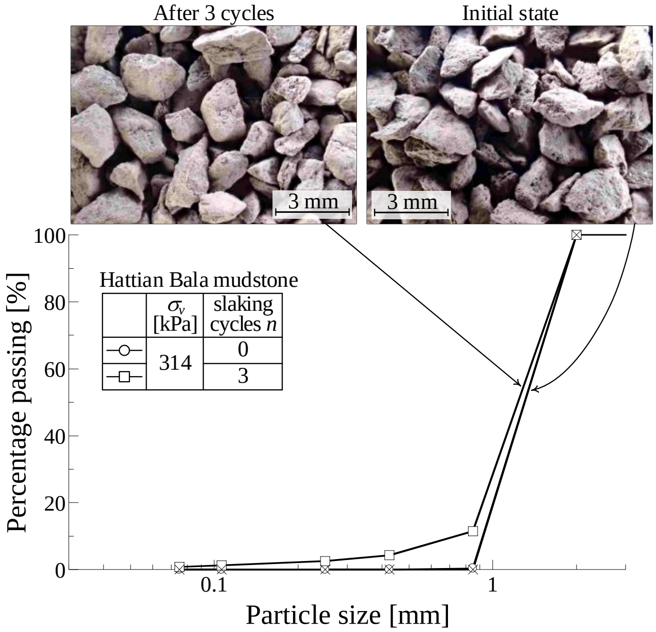
The particle size distribution of the three types of crushed mudstones in their initial state, after compression and after different numbers of wetting and drying cycles, are shown in Fig. 8. The test results for the crushed Kakegawa and Kobe mudstones under a vertical effective stress σ_v' of 314 and 1256 kPa are shown in Fig 8(a) and 8(b), respectively, whereas the results for the crushed Hattian Bala mudstone under a vertical effective stress σ_v' of 314 kPa are provided in Fig.8(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. 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.



(a) Kakegawa mudstone



(b) Kobe mudstone



(c) Hattian Bala mudstone

Fig. 8. Change in particle size of three mudstone types during one-dimensional compression slaking testing

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 Hattian Bala mudstone particles did not contain any intragranular pores (Fig. 3(e)), which would explain why there is so little change in particle size distribution during wetting and drying cycles. 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 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 and causing volumetric compression without noticeably changing the maximum particle size.

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 (Muir Wood, 2007), defined by the ratio of areas ABC and ABD in Fig. 9 (Muir Wood, 2007; Kikumoto, 2010). 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 Fig. 9(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 Br 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.

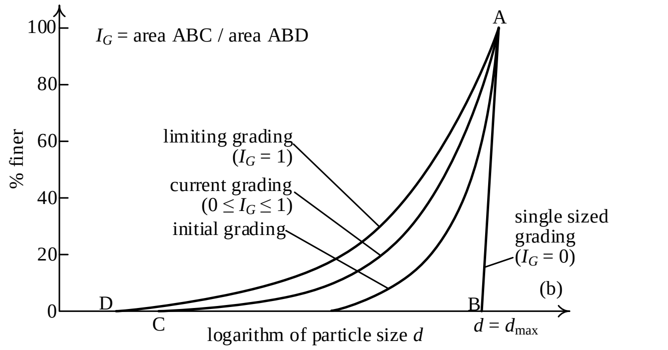


Fig. 9. Schematic diagram of grading evolution and definition of a grading state index IG based on the ratio of areas ABC and ABD (Muir Wood, 2007; Kikumoto et al., 2010)

Figures 10, 11 and 12 show 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. The upper figures (figure parts (a) and (b)) illustrate the behavior in compression, whereas the lower figures (figure parts (c) and (d)) show the variation in grading. From the behavior of the crushed Kakegawa mudstone shown in Fig. 10, it is clear that the value of Br (Fig. 10(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 (Miura & O-Hara, 1979; McDowell et al., 1996). After the wetting and drying, the Br value increased from 0· 21 to 0· 24 (Fig. 10(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 Fig. 11, the increase in B_r 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.

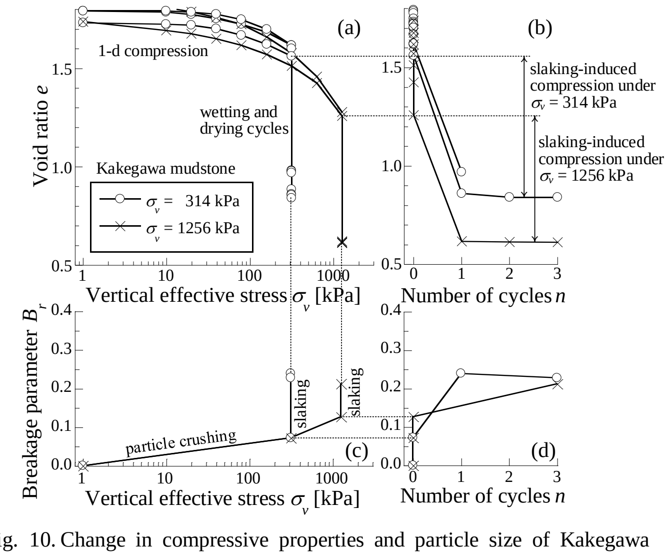


Fig. 10. Change in compressive properties and particle size of Kakegawa mudstone during one-dimensional compressive slaking testing

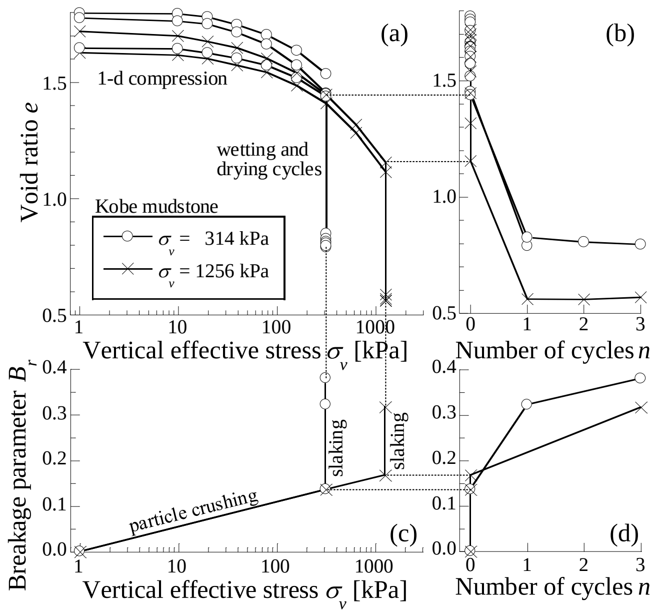


Fig. 11. Change in compressive properties and particle size of Kakegawa mudstone during one-dimensional compressive slaking testing

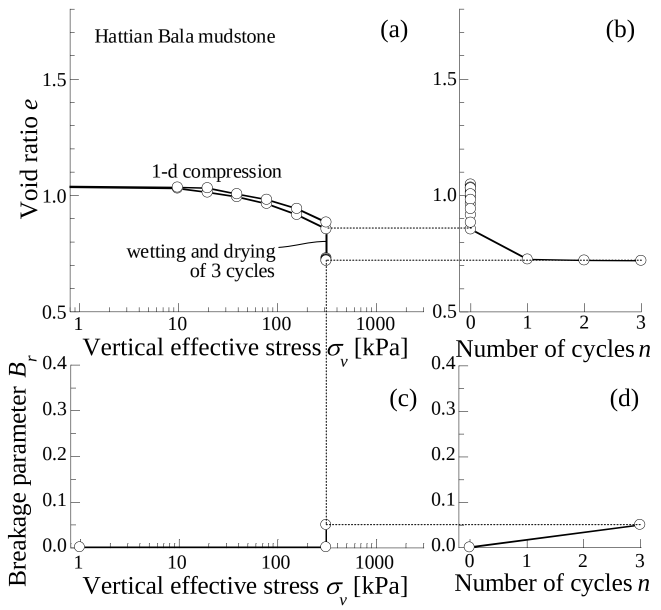


Fig. 12. Change in compressive properties and particle size of Kakegawa mudstone during one-dimensional compressive slaking testing

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 mudstone.

V. CONCLUSIONS

Accelerated slaking tests, newly proposed one-dimensional compression slaking tests and other laboratory analyses were conducted in conjunction with SEM observation and XRD analysis to study the slaking of granular fills derived from mudstones and its influence on their deformation behavior. Through this, it has been shown that different mudstone types have 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 packing density. Moreover, the evolution of 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.

ACKNOWLEDGEMENTS

The authors wish to thanks to the Earthworks Research Section of the Nippon Expressway Research Institute Company Limited for providing mudstones specimens and the former member of Kikumoto Laboratory. The first author is grateful to the financial support provided by the Indonesia Endowment Fund for Education (LPDP), Ministry of Finance Republic of Indonesia and the University of Lampung. This work was also supported by JSPS KAKENHI Grant Numbers 20860045, 22760355, 24360192 provided to the second author.

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