VERTICAL STRAIN AND BREAKAGE BEHAVIOUR OF CREEP LOADED MUDSTONE IN WEATHERING CYCLE

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ABSTRACT: Mudstone is sensitive against to cyclic wetting and drying, known as slaking. The mudstone is one of the widely available materials for the construction of dam embankment, which is exposed to wetting/drying cycle and water gradient due to the fluctuation of the water level. The settlement is one of the major problems in a mudstone's embankment, which can be induced by slaking as well as suffusion (small particle washout by water gradient). To examine the slaking and the suffusion effect on a vertical strain of the mudstone, a series of modified oedometer tests were conducted on the crushed mudstone by applying wetting/drying as well as water gradient cycle. After the wetting stage completed the water gradient was applied to washout the particle then drying process continued under the creep loading of $\sigma v = 500$ kPa. It was noticed that first wetting triggered the larger settlement and gradually reduced in the consecutive cycles. The wetting began to show the expansion after the 5th cycle. The drying caused settlement continuously. The washed-out particles by applied water gradient were limited after the 8th cycle. A gradual increase in the particle breakage also was monitored with increasing number of cycle.

Key Words: *Slaking, Settlement, Deformation, Suffusion, Particle breakage.*

INTRODUCTION

Mudstone strength and deformability characteristics are dependent on wetting and drying cycle, known as slaking. The settlement is one of the major problems, induced by the slaking. Slaking of the mudstone was pointed out as one of the causes for the collapse of embankments by Surga Bay earthquake 2009 (Takagi et al.,2010). Similarly, Ataturk Dam (Turkey) is a clay cored rock-fill dam, constructed in 1990. When the reservoir level started to rise, settlement experienced along the crest, Mella et al. (2007) reported that both vertical and horizontal displacement still took place even for 15 years after the construction under more or less constant loading condition. Thus, mudstone embankment's long-term stability and settlement problems may possibly arise from the occurrence of the slaking due to the repeated wetting and drying cycles.

The slaking also causes particle breakage and particle shape changes. In addition, at a dam embankment, when the water level rises not only causes the wetting but also increases the water gradient. So, suffusion (finer particle washed out by water gradient) susceptibility also increases with a number of wetting/drying & water gradient cycles. Even though vertical strain behaviour by wetting and drying

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cycle has been analysed in previous studies (i.e.Zhang (2014)), combined effect of slaking and suffusion behaviour has not yet been addressed in the literature.
Further, Zhang (2014) found that apart from the dry and wet cycle, temperature also a governing factor in causing the vertical strain. Thus, in present study wetting and drying cycle was coupled with heating and cooling cycle to simulate the actual field condition.
Therefore, new weathering test apparatus was developed herein to study the vertical strain behaviour of the crushed mudstone under the coupling action of wetting at the lower temperature (room temperature (25^0c)) and drying (dry (wc<1%) at 56^0c. A typical cycle starts with wetting subsequently water gradient and drying (hereafter called as weathering cycle).

PARTICLE BREAKAGE

Particle breakage is one of the major consequences in the slaking. Slaking potential indexes such as slaking durable index (Id1 & Id2), slaking index JGS 2125-2006, slaking ratio (NEXCO-100,2006) and static slaking are measured by particle breaking behaviour.

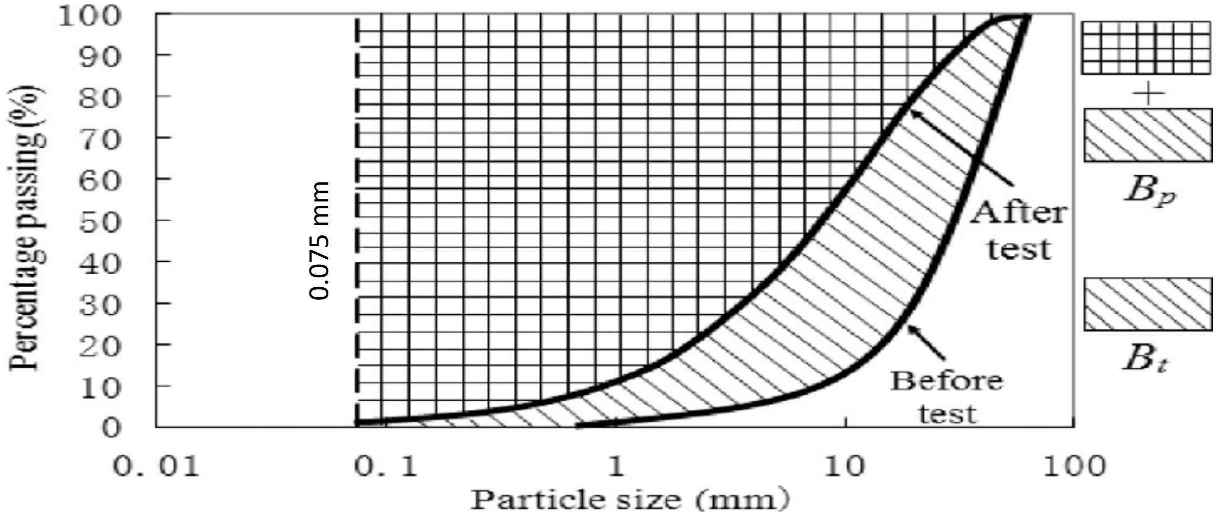


Figure 1. Definition of relative breakage (Hardin,1985)

The present paper, the Relative Breakage (subsequently abbreviated as Br) developed by Hardin (1985), is introduced to assess the extent of particle breakage. Figure 1 graphically explains the assessment of the Relative Breakage (Br). At Figure 1 the area between initial grain size distribution curve (denoted as Before test) and the grain size distribution curve after loading (denoted as After test) can be called the total breakage B_t (represented by symbol in Figure 1)
The area between initial grain size distribution curve and the vertical line of 0.075 mm is regarded as the breakage potential Bp represented by ( ) symbol in Figure 1. The relative breakage Br is defined as a ratio of the total breakage Bt over the breakage potential Bp. In the present paper, particle breakage pattern was analysed with numbers of drying/wetting cycles as well as loading.

MATERIAL

Hammamatsu mudstone used in this investigation was collected from the reclamation site slope in Hammamatsu city, in Shizuoka Prefecture. The collected material was mainly broken by mechanical crushing and sieved to obtain the particle size of 2-4.75mm.

The sieved material (2-4.75 mm) was used for the specimen preparation. The specimen (φ=75mm & h=150mm) was prepared into the mold as five layers by applying external vibration (applying wooden hammer) to avoid breakage in the initial grain size. Initial density of 12.16 kN/m^3 (Dc=78% of the initial material) was kept constant for all the specimen. The Hamamatsu mudstone, which can be categorized as medium durable rock according to the Slaking Durable Index of Id1=92.13% & Id2=73.75%, Slaking Index JGS 2125-2006 of 3, Slaking Ratio (NEXCO-100,2006) of 0.87% and water absorption (ASTM method C97) of 12.7%, which were conducted herein. In total 7 specimens (each specimen weight is 3300g) were prepared and subjected to different extent of lading and weathering cycle.

DEVELOPMENT OF WEATHERED MUDSTONE APPARATUS

Measuring of vertical strain in weathering cycle of mudstone is much more complex than that of conventional oedometer testing. Slaking process needs be accelerated to measure within laboratory condition and required time frame. Three variables such as water content, temperature, and water gradient want to be controlled to simulate the actual conditions. Figure 2 (a) shows the modified oedometer that consists of main three components such as heating/cooling system, drying/wetting system and water gradient & drain out system. Figure 2 (b) explains the typical weathering cycle's steps, it starts at wetting at step 1, subsequently applying the water gradient at step 2 (5 litres of water in 300 kPa) and drying in stpe3.

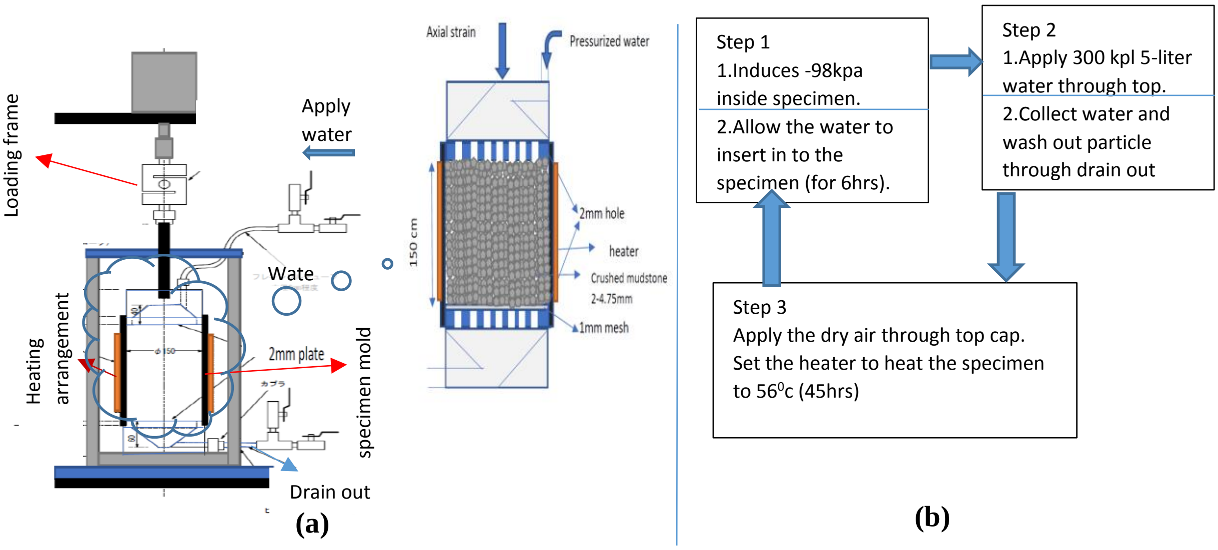


Figure 2. (a) Schematic diagram of weathering apparatus **(b)** Typical steps in a weathering cycle

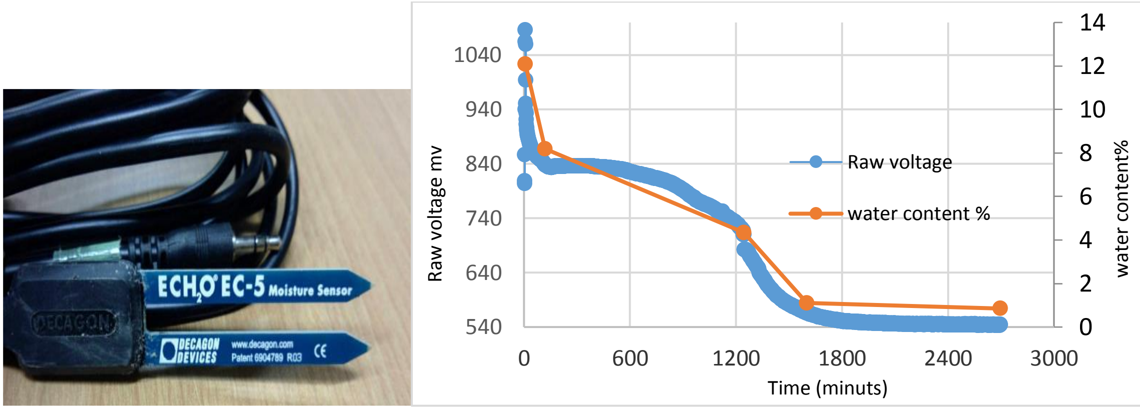
Heating/cooling system.

Temperature influences in the volumetric changes of the mudstone was explained by Towhata et al (1993) and Paaswell (1967), by whom volumetric changes in the oedometer were recorded in the temperature variation. In the present study, specimen mold was wrapped by the heater, by which temperature can be controlled up to 100^{0}c. For the calibration, a thermometer was inserted inside of the mudstone specimen and change the heater's temperature (at outer surface) to set the inside average temperature as 56^{0}c (as calibrated, outside temperature was found as 60^{0}c).

Wetting and drying system

For wetting, negative pressure (-98kPa) was applied inside of the specimen then water was allowed to enter into the specimen. Wetting was prolonged until vertical strain become constant (vertical strain became as constant after 6 hours at calibration). Figure 3 (a) shows the moisture sensor, by which water content can be detected on time by measuring the voltage differences in between the two sensors.

Moisture sensor was inserted into the specimen to measure the moisture reduction at the drying phase, at which dry air was applied through the top cap and simultaneously specimen temperature increased to the average of 56^0c. Moisture sensor reading is continuously monitored. Moisture sensor's raw voltage is correlated to the water content. Figure 3 (b) explains the raw voltage changes during the time of applying dry air and increased temperature, raw voltage values converted to the water content (%) by doing calibration at actual stressed condition.



(a) (b)

Figure 3. **(a)** Moisture content sensor **(b)** Raw voltage/water content(%) vs time.

Water gradient & drain out system.

After the wetting, water gradient (300 kPa) was applied through the top cap. water and washed out particle were collected through the bottom. Those particles were oven dried and measured the weight in cycle by cycle.

TEST PROCEDURE

Three series of testing were conducted. Table 1 explains the series name, the specimen numbers and the testing condition.

Table 1. Tested specimen

Series	Name of specimen	Loading condition In kPa	No Dry and wet cycle
Series 1	L200	200	0
	L300	300	0
	L500	500	0
Series 2	L-Wc-01	500	1
	L-Wc-03	500	3
	L-Wc-05	500	5
	L-Wc-12	500	12
Series 3	D/W-01	0	01
	D/W-03	0	03
	D/W-12	0	12

*(series 1) L-loading, (series 2) L-Wc-loading and weathering cycle, (series 3)D/W- dry and wet cycle

Three series of testing can be explained as follows.

Series 1: To find the breakage behaviour with vertical loading
3 specimens (L200, L300 and L500 as named at Table 1) were prepared and loaded to 200, 300, and 500 kPa respectively. After the vertical strain becomes constant, remaining mudstone at mold was sieved and relative breakage (Br) was measured.

Series 2: To find the vertical strain behaviour of the mudstone, exposed to weathering cycle.
At this series of experiment, vertical loading kept as constant (500 kPa), 4 specimens (L-D/W-01, L-D/W-03, L-D/W-05 and L-D/W-12) were prepared and subjected to 1, 3, 5 and 12 weathering cycle respectively.
Vertical strain with the weathering cycle tests were conducted through following steps (these steps graphically depicted by Figure 1(b)); **steps-0** applying 500 kPa as axial stress, keep it as constant for the entire test. **Step-1** after the axial strain becomes constant at step-0 (which calibrated as 6 hours) wetting step to be started. Water is applied to the top cap by inducing negative pressure (-98kpa) inside of the specimen and wait until the vertical strain becomes stable (at calibration, the wetting time defined as 6 hours). **Step-2** water gradient (300kpa) applied through the top cap and collect the water and washout particle through the 1mm mesh. Each cycle was applied 5 litres of water at this stage. In the drying phase as **step-3**, pressurized dry air has been applied through the top cap. At the same time, the heater maintained the inner specimen's average temperature as 56^0c. The required duration of applying dry air and heating arrangement were calibrated for reducing the water content less than 1% (2700 minutes, as calibrated in Figure 3(b)). **Step-4** After finishing 4 experiments, remaining mudstone was sieved and analysed the relative breakage (Br).

Series 3: Breakage behaviour unconfined wet/dry cycle
3 specimens (UC-D/W-01, UC-D/W-05 and UC-D/W-12 as explained by Table 1) were prepared and subjected 1, 5 and 12 numbers of dry /wet cycle respectively without vertical loading. After that remaining material sieved and relative breakage (Br) was measured.

RESULTS AND DISCUSSION

Results of series 1
In series 1, three specimens (MS001, MS002 & MS003 as explained in Table 1) were subjected to vertical stress respectively 200, 300, 500 kPa. After the strain gets stabled, remaining material was sieved and breakage (Br) was measured. Figure 4 (a) shows the vertical strain and stress relationship as well as relative breakage (Br) pattern in stress and strain increment. Figure 4(b) shows the particle gradation curve before and after loading.

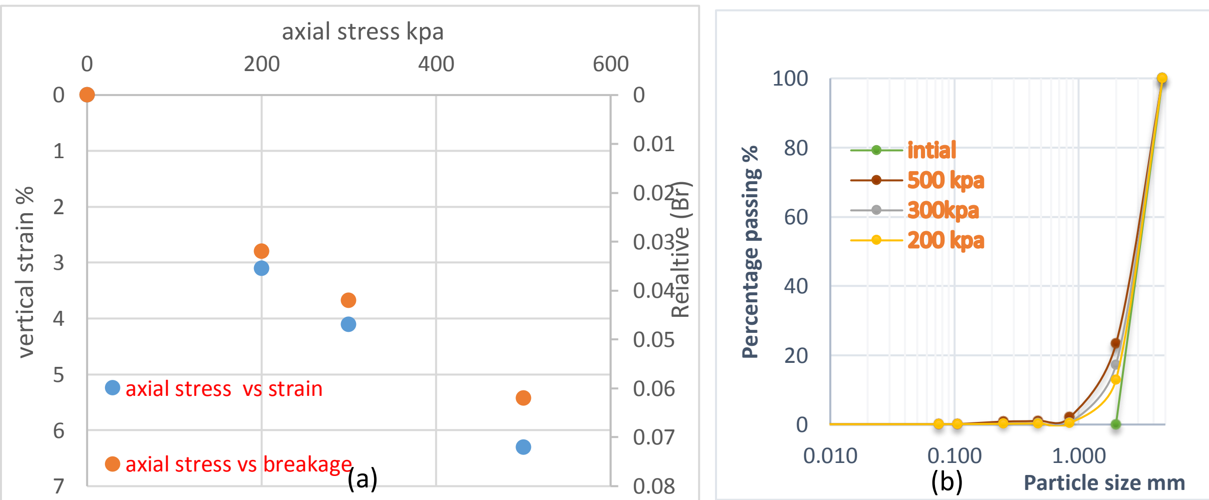


Figure 4. **(a)**Vertical strain & Br vs axial stress**(b)**Particle size distribution

At here (Figure 4(a)), vertical strain and relative breakage (Br) have linearly relation with vertical loading within the tested loading range. At Figure 4(b) explains the particle size distribution of the initial and after loading. Loading does not cause any noticeable degradation in the bigger particle's percentage (even after the 500 kpa, more than 75% of particle are still bigger than 2mm). But percentage of smaller particle was noticeably increased. This behaviour also was found by the experiment done by Kikumoto et al (2010) as the major effect of particle crushing is to increase the proportion of fine particles which fill the voids between larger particle without particularly changing the size of the largest particles.

Results of series 2

At series 2, mudstone specimens were subjected to vertical loading (500 kPa) as well as weathering cycle. Four samples were prepared and exposed to weathering cycle as mentioned in Table1. In a cycle, the vertical strain was measured immediately after wetting (W) & drying (D) at each cycle.

Vertical strain behaviour along weathering cycle is depicted in Figure 5, in which wetting state representing by filled circle whereas, dry state representing by the open circle. Vertical strain induced by wetting at nth cycle denoted by nthW, as well as drying strain donated by nthD at Figure 5. Wetting (1st w) at 1st weathering cycle caused higher vertical strain (about 15%) compare with consecutive weathering cycle due to the collapse behaviour. The vertical strain became stable after the 9th weathering cycle. Further induced settlement densified the specimen (more than 35% of initial density) up to 9th cycle.

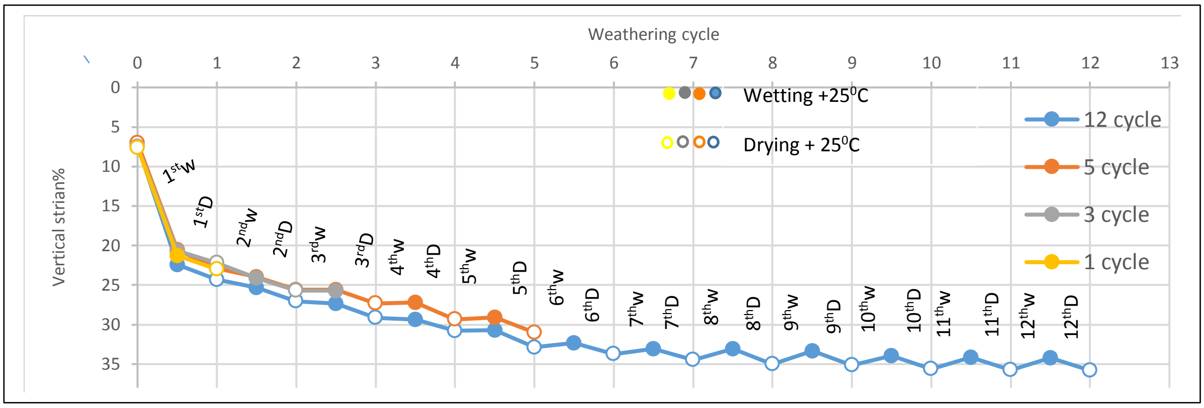


Figure 5. Wetting and drying cycle vs vertical strain

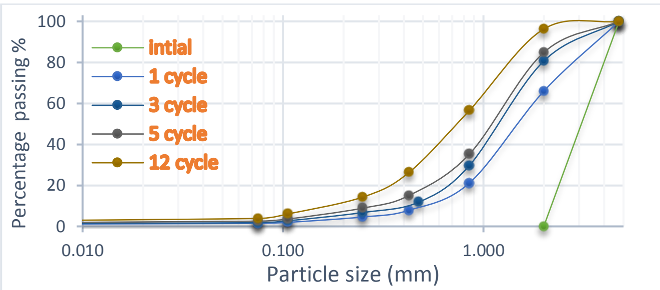


Figure 6. Breakage with cycle

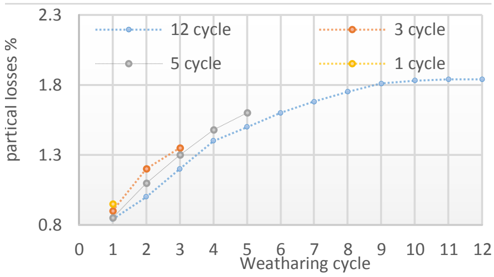


Figure 7. Cycle vs particle losses

Wetting caused settlement (positive vertical strain) in only for first three cycles. After 5th cycle, it showed an expansion behaviour because swelling potential increases with weathering cycles. Finally, the expansion behaviour became stable after 7th cycle. The remaining mudstone in five samples was sieved and particle size distributions were plotted as depicted in Figure 6. The particle size distribution severely changed by the breakage that triggered by weathering cycle compared with loading breakage

(Figure 4(b)). This breakage increases the percentage of the finer particle and reduced the bigger particle (after the first cycle only 35% of the particles were remained more than 2mm size in Figure 6).
Particle losses (%) along weathering cycle is explained by Figure 7. Washout particles by water gradient were collected and over dried, whose was measured. After the 9th cycle particle losses were limited. It can be explained as densification was caused by settlement (as shown in Figure 5) and finer particle produced by the breakage (as shown in Figure 6) made the clogging effect, by which the finer particles retained and trapped in between bigger particles. Thus, particle losses limited after the 9th cycle.
Figure 8 explains the relationship between the vertical strain and relative breakage (Br) at series 1 and series 2. At loading (series 1) breakage and vertical strain has a linear relationship. The first cycle caused the collapse, by which severe breakage and settlement took place.

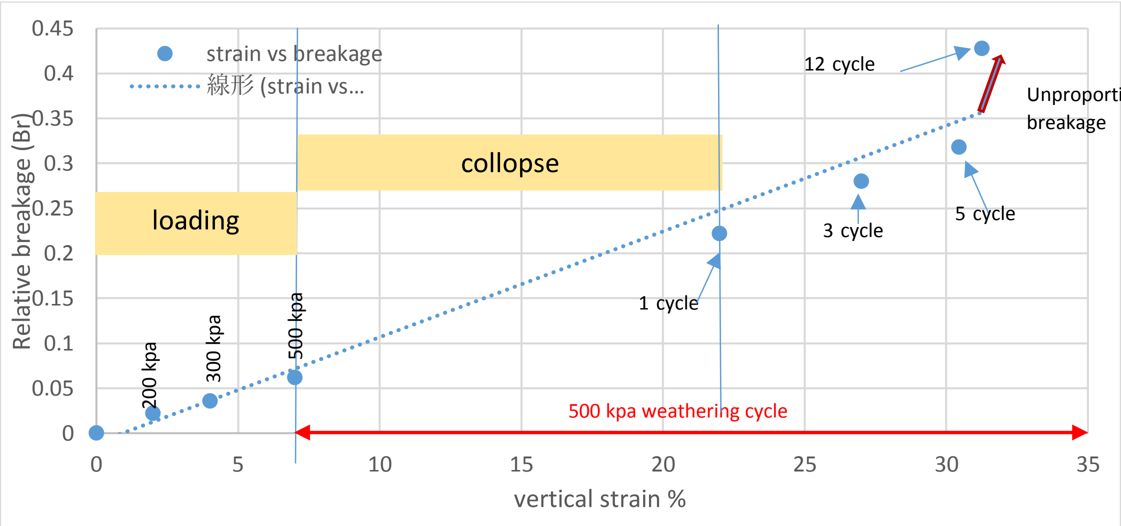


Figure 8. Vertical strain vs relative breakage (Br)

Further, 3rd and 5th weathering cycle also caused gradual increases in vertical stain as well as relative breakage (Br). But, in 12th cycle severe relative breakage was recorded, whilst axial strain was not developed proportionately with relative breakage (Br).
Due to the densification, particles were not allowed to rearrange. Thus, even particle size was reduced vertical strain was not developed proportionately with the recorded relative breakage (Br).
Weathering cycle limited the vertical strain after 9th cycle but it seemed to continue the particle breakage in continuing cycle after that.

Results of series 3

In series 3, three specimens (D/W-01, D/W-05, and D/W-12) were prepared and applied the wetting and drying cycle respectively 1,5, and 12 without any vertical loading. Particle size distributions are shown as below in Figure 09, by which particle gradation curve is illustrated at before and after the weathering cycles. Even after the 5 cycle, all the particle's size become less than 2mm as shown in Figure 9. Further it shows percentage of the bigger particle was severely reduced compared with breakage behaviour at series 1 and series 2.
Fig 10 shows the difference in between breakage occurred in series 2 and series 3 condition. In confined stress and weathering cycle condition (series 2-at 500 kPa) produced higher smaller particle compared with unconfined condition (series 3). But in reduction in bigger particle's percentage showed opposite behaviour.

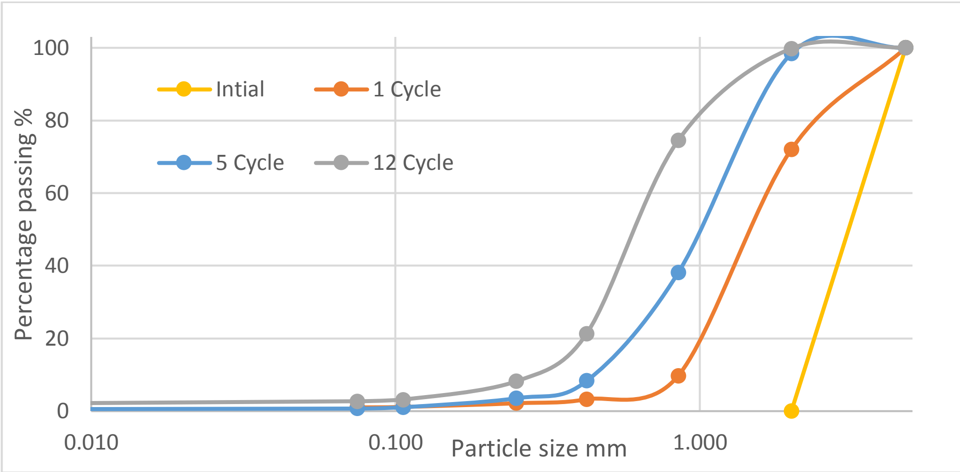


Figure 9. Unconfined breakage with cycle

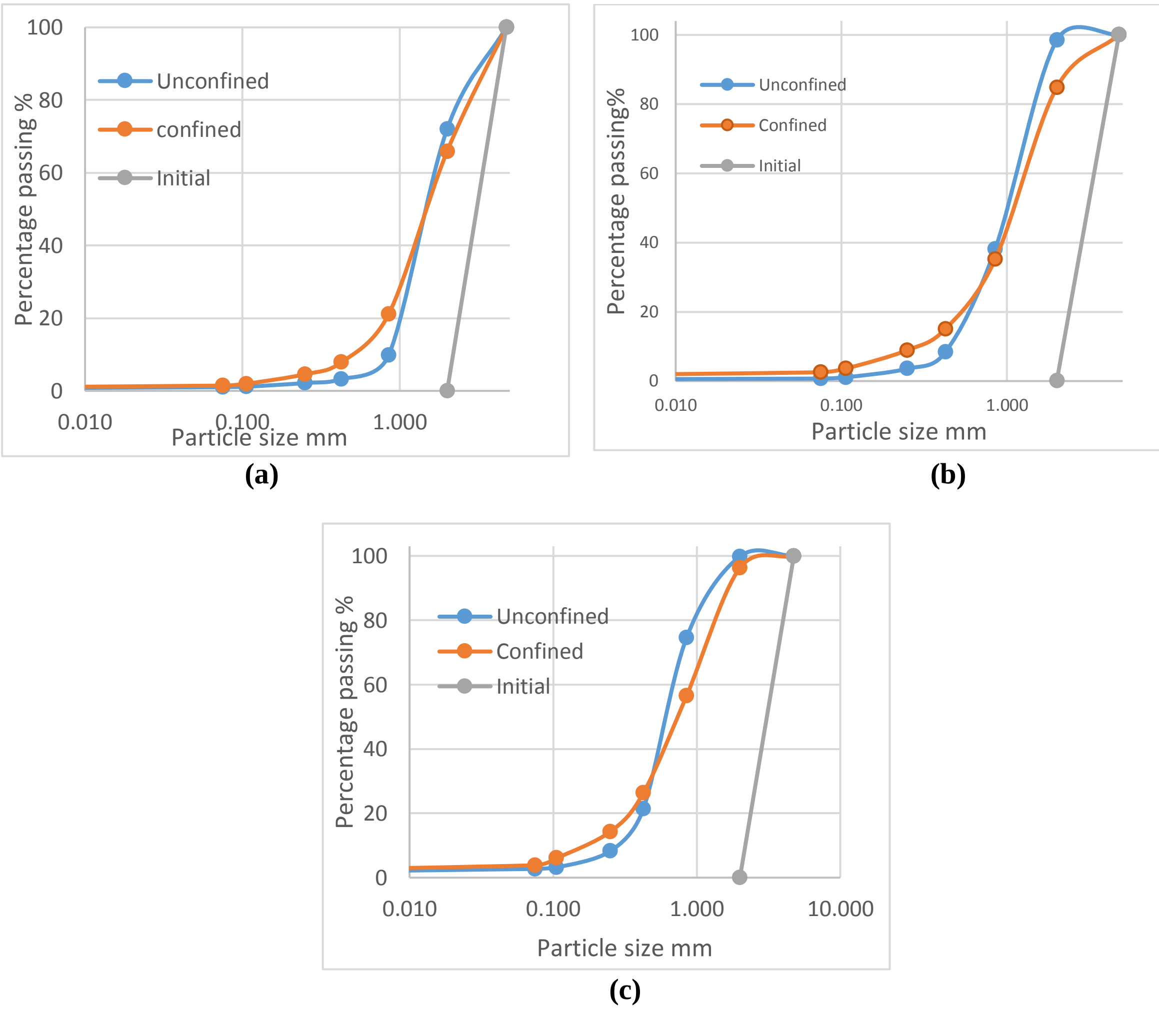


Figure 10. particle grain distribution in confined and unconfined condition **(a)**1 cycle **(b)** 5 cycle **(c)**12cycle

CONCLUSIONS

Experimental results show that wet/dry cycle caused an increase in vertical strain as well as particle breakage. The particle losses by the water gradient also increased along with wetting and drying cycle. However, the vertical strain and particle losses by the water gradient gradually reduced in increasing wet/dry cycles.

Particle breakage shows the linear behaviour with strain development in loading, but after the coupler weathering cycles vertical strain development was severely reduced, but particle breakage continues.

Particle breakage shows significant different at confined and unconfined condition, these phenomena to be considered in assessing the slaking indexes.

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