EFFECT OF SLAKING ON THE ENGINEERING BEHAVIOUR OF THE CRUSHED MUDSTONES

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ABSTRACT:

Among the different types of soft sedimentary rocks, mudstones is sensitive against to cyclic wetting and drying known as slaking, leading to significant physical degradation even after one cycle of wetting and drying. In order to examine slaking effects on engineering behaviour of crushed mudstone, a series of direct shear tests were conducted on the crushed mudstone by simulating cyclic wetting and drying under different stress conditions by using a modified direct shear apparatus. It is noted that the creep shear deformation in the first wetting becomes larger as increase in the stress ratio, while it decreases with the progress of cyclic wetting and drying. During the drying process, initially, no appreciable creep deformation is found to occur at higher water content. When the water content of specimen has reached about 2.5 %, both vertical and shear deformations occur progressively with water loss. A gradual decrease of the peak angle of friction is observed with the increasing number of cycles.

Key words: Direct shear test, Slaking, Shear strength, Deformation

INTRODUCTION

Mudstone tends to slake and soften when in contact with water and has given rise to numerous slope stability problems (Regues et al., 1995), coal mine roof falls, shale embankment failures (Bragg and Zeigler, 1975) and loss of bearing capacity of foundation (Mochizuki et al., 1985) around the world. For example, the landslide dam formed by the 2005 Kashmir earthquake was breached in 2010 during moderate rainfall. It is assumed that the dam was breached due to the slaking of mudstones (Kiyota et al., 2011). In addition, slaking of filling mudstone was pointed out one of the causes for collapsing of embankment by Suruga Bay earthquake 2009 (Takagi et al., 2010). Similarly, the Ataturk Dam, Turkey is the fourth largest clay cored rock-fill dam in the world, constructed in 1990. When the reservoir level started to rise, settlement problems started to occur along the crest reaching considerable level. Malla et al. (2007) reported that both vertical and horizontal displacements were still taking place even after 15 years of construction under more or less constant loading conditions. The vesicular basal rock used in the cross-section of the dam was found to be slaked (Cetin et al., 2000). Moreover, when high embankment made of these materials is considered, long term stability and settlement problems may possibly arise from the occurrence of slaking of geo-materials due to repeated wetting and drying cycles (Cetin et al., 2000; Tovar et al., 2011).

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The slaking causes particle size reduces and shape changes with significant reduction in shear strength and increase in deformation. The strength and deformation behaviour of such geo-materials becomes very complex as different factors such as the water content before wetting, the number successive cyclic wetting and drying, density of geomaterials and finally particles crushing largely affects the overall behaviour. So, many geotechnical problems specifically on mudstone have demonstrated that conventional methods typically used in geotechnical engineering practice are not adequate for stability analysis of such unique geomaterials.

It is necessary to evaluate the durability of such rocks against wetting and drying, their effects on physical and mechanical properties, and ultimately the stability of the natural and artificial slopes. Slaking of mudstone has been studied by many researchers (e.g., Ladd, 1960; Nakano, 1967; Franklin and Chandra, 1972; Moriwaki, 1974 and Botts, 1986 etc.). Nakano (1967) conducted a research on the breaking of tertiary mudstone with slaking and observed the changes in soil properties. Most of these researches are related with the change in physical properties such as density, particle size distribution etc. of mudstone due to slaking, do not deal with mechanical properties. Similarly, a large creep deformation and reduction in the peak shear strength of crushed mudstone after immersion was reported by many authors (e.g., Kiyota et al., 2011 and Yoshida et al., 2002). Some researchers tried to evaluate the impact of slaking on the engineering behaviour of mudstones under unconfined condition. However, cyclic wetting and drying in the field typically occurs under anisotropic stress condition. Therefore, in order to predict the long term response of various natural slopes and other geotechnical structures, a better understanding of the strength and deformation characteristics of geomaterials undergoing slaking is essential. So, the author tries to achieve a better understanding of slakable geo-materials through this research.

In this study, a series of direct shear tests were performed with the advanced direct shear apparatus under different stress ratio, R. Specimens were consolidated at prescribed stress ratio, R, then they were wetted and dried alternatively under constant shear loading and finally monotonic shear load was applied after third wetting to observe shear strength and deformations characteristics. Sieve analysis was also performed to investigate the changes in particles size distribution and degradation index.

MATERIAL AND EXPERIMENTAL PROCEDURE

The Hattian Bala mudstone used in this investigation was obtained from the earthquake induced landslide dam, formed by the 2005 Kashmir earthquake, which is located southeast of Muzaffarabad, Pakistan. As already mentioned, the earthquake induced landslide dam was suddenly breached on 9th February, 2010 just after moderate rainfall preceded by drought. Slaking of mudstone was assumed to be one of the major causes of the failure (Sattar et. al., 2010 and Kiyota et. al., 2011). From a geological point of view, the source area is formed of Miocene aged Murree formation (Mirza et. al., 1996), composed of alternate layers of mudstone and sandstones with minor intercalations of limestone and conglomerates indicating its fluvial deposition environment. The fine grained mudstones are mostly deep red in color as shown in Fig. 1, being indicative of high iron contents. The specimens of oven dried crushed mudstone were prepared by removing particles finer than 2 mm and larger than 4.75 mm as a necessary adjustment to the apparatus dimension. The specimens were not thoroughly compacted to prevent from particle breakage and to make similar conditions as those of the landslide dam, which was dynamically deposited without strong compaction. The slaking index (JGS 2132) of the mudstone was evaluated as level 1, while the slaking ratio (NEXCO-110, 2006) was 96.86 %.

The performed laboratory tests comprise a series of direct shear tests with a modified direct shear apparatus in order to examine effect of slaking on engineering behaviours of crushed mudstones. A

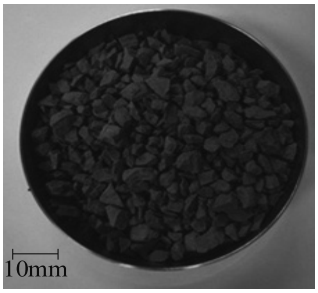

Fig.1 Hattian Bala mudstone

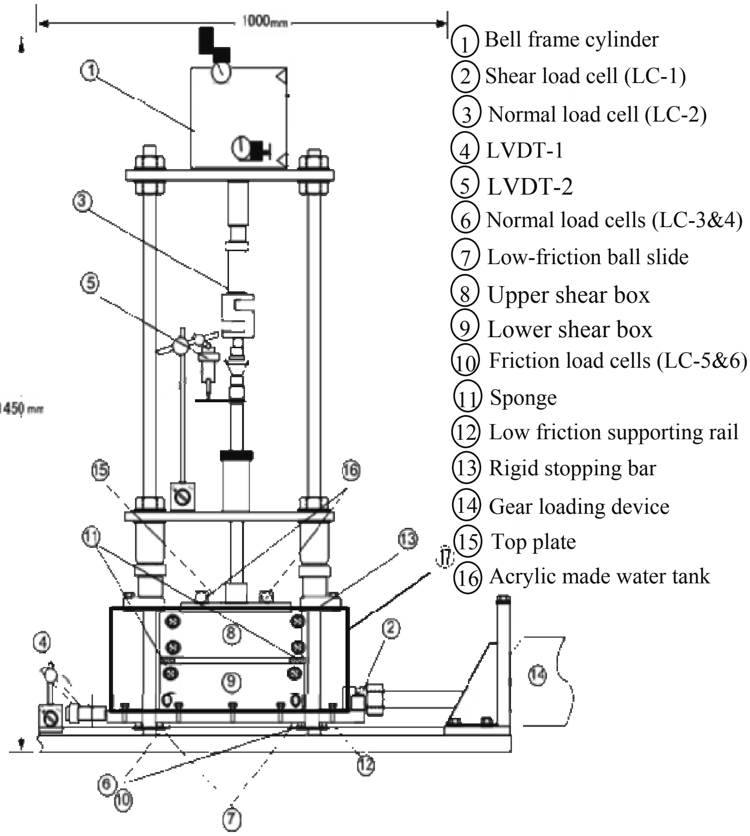

Fig. 2 Schematic diagram of modified direct shear apparatus

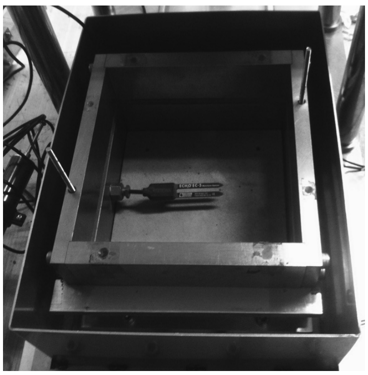

Fig. 3 Moisture sensor and larger container outside of shear box

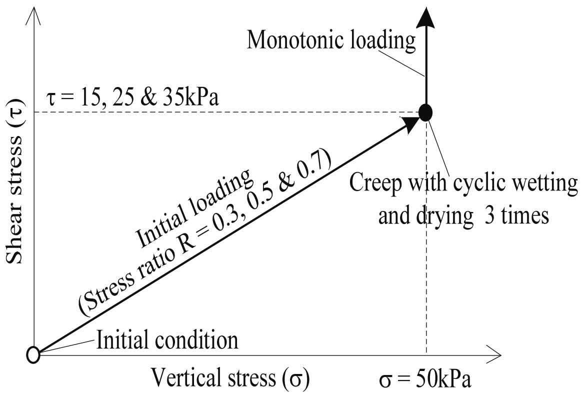

Fig. 4 Stress path

schematic view of the modified direct shear apparatus used in this study is shown in Fig. 2. The inside specimen size is 20cm x 20cm x 9.14 cm. The initial opening between upper and lower boxes was fixed as 10 mm. The apparatus has the following essential features: 1) a possible feedback control on both normal load and shear load to impose any prescribed stress path in the shear stress-normal stress space; 2) a lower shear box moving on a very low-friction rail, with two friction load cells to evaluate any friction at the bottom of the lower shear box; 3) shear load applied by a high precision gear loading device driven by a servo-motor, allowing easy and exact control of arbitrary shear displacement ratio as well as sustained loading (by a feedback control on the shear load). The importance of all these features to obtain reliable data of direct shear tests on granular material was demonstrated by Shibuya et al. (1997). A moisture sensor was inserted into shear box to measure the water content of the specimen instantaneously as shown in Fig. 3.

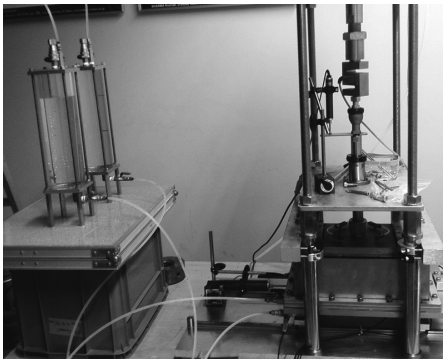

Fig. 5 Experimental setup to saturate specimen inside the shear box

Fig. 6 Shear box covered by silica gel and temperature and humidity measurement

In this study, loading process during the test consisted of three stages as shown in Fig. 4: 1) the specimen was subjected to shear and average normal stresses keeping their ratio, R (= τ/σ_v) constant (R= 0.3, 0.5 and 0.7). Both shear stress (τ) and normal stress (σ_v) were steadily increased up to respectively 15 kPa and 50 kPa for R= 0.3, 25 kPa and 50 kPa for R= 0.5 and 35 kPa and 50 kPa for R= 0.7; 2) After the prescribed shear (τ) and normal stress (σ_v) values were reached, these values were kept constant until the stabilization of both shear and vertical deformations are achieved. After both shear and vertical deformations stabilization, the first wetting was carried out by supplying distilled water from the bottom of shear box until the specimen was fully immersed. Two cylinders with valves were used to control the water flow inside and outside of the shear box as shown in Fig. 5. The overflow of water was collected by fixing an external container around the shear box as shown in Fig. 3. This creep loading process represents a situation that slope ground is saturated by rain fall under constant stress condition. When deformation due to immersion led to stabilize, water was drained out (the first drying). Dry air was pumped from the bottom of the shear box and the shear box was covered by silica gel (Fig. 6) to absorb moisture from specimen while room temperature was maintained at 30°C. When both shear and vertical deformations as well as water content had reached an almost constant value, water was supplied again to the specimen (the second wetting). The same process of drying and wetting was repeated (the second drying and the third wetting); 3) After the third wetting and deformations stabilization, a monotonic shear loading was applied at a constant rate of shear deformation (0.2 mm/min) under constant normal stress (σ_v) until the specimen reaches the residual state. A series of the monotonic loading tests on dry and saturated specimens were also performed to compare strength and deformation characteristics with those of the cyclic wetting and drying creep test. After completing direct shear test, the tested sample was dried in oven and sieve analysis was performed.

Table 1: Basic properties of tested specimens (Hattian Bala crushed mudstone)

Sample	Stress ratio during creep, R	Initial density (g/cm^3)	Density before ML (g/cm^3)	Test condition during creep and Monotonic loading (ML)
MS001	0.3	1.482	1.508	Creep with cyclic wetting and drying for 3 times and ML under saturated condition
MS002	0.5	1.529	1.549	Creep with cyclic wetting and drying for 3 times and ML under saturated condition
MS003	0.7	1.553	1.577	Creep with cyclic wetting and drying for 3 times and ML under saturated condition
MS004	0.3	1.478	1.491	Creep & ML under dry condition
MS005	0.5	1.558	1.567	Creep & ML under dry condition
MS006	0.7	1.556	1.565	Creep & ML under dry condition
MS007	0.3	1.479	1.518	Creep (dry and wetting) & ML under saturated condition
MS008	0.5	1.529	1.549	Creep (dry and wetting) & ML under saturated condition
MS009	0.7	1.529	1.569	Creep (dry and wetting) & ML under saturated condition

TEST RESULTS AND DISCUSSION

Figure 7 shows the instantaneous response of creep deformations and water content of the specimen during the wetting and drying cycles under stress ratio (R) 0.5. Each cyclic wetting and drying creep test took about one month to complete. The influence of wetting in the first cycle upon shear deformation appears to be significant for all specimens. Similarly, negative vertical deformation (expansion) occurs due to wetting. Positive value of vertical deformation is taken as contraction. This expansive behavior of crushed mudstone would consist of two phases, swelling caused by water absorption of clay mineral and dilatancy due to shearing.

For the second and third wetting processes, the increment of shear deformations are relatively small, almost 1/8 times the increment of shear deformation in the first wetting. However, substantial negative vertical deformation occurs during the second and third wetting processes. Figure 7 also shows that water content decreases gradually during the first and second drying processes. Initially, no appreciable creep deformation is found to occur at higher water content. When the water content becomes about 2.5 % (point A and B in Fig. 7), both vertical and shear deformations occur progressively with water loss and finally tend towards an asymptotic value at water content of about 0.7 %. As seen from the Fig. 7, both creep curves during drying are composed of two well defined curvilinear parts. Figure 8 shows schematic sketch of crushed mudstone particles which consist of two pore systems, inter (macro) and intra-primary (micro) porosity (Braudeau et al., 2004). It is assumed that water leaves the crushed mudstones from the inter-pedal (macro) pores causing shrinkage of inter-pedal (macro) pores (first part of curvilinear). When the inter-pedal (micro) pores empty out, intra-primary (micro) pores begin to shrink, losing its water content (second part of curvilinear). The shear deformation during first wetting is found dependent on initial density of specimen before wetting as shown in Figure 9.

The above test results are summarized in Fig. 10, showing the increment values of creep shear and vertical deformations at each stress ratio, R. The wetting-induced maximum creep shear deformation of 3.4 mm was observed at R= 0.7 during the first wetting (see Fig. 9a). Similarly, wetting-induced creep failure was observed at R= 0.8 on the same material as the one in this study. Therefore, it seems that the creep shear deformation during wetting is proportional to the value of R, which would indicate high risk of slaking-induced instability at steep slopes.

Panabokke and Quirk (1956) reported that the slaking level of clay aggregates became higher as the initial water content of the specimen became lower. Therefore, it can be understood that the maximum deformation was observed during the first wetting because the specimen in this study was prepared by oven-dried crushed mudstone. Figure 7 a) shows a larger shear displacement during the first wetting phase, compared to the second and third wetting. This can be explained by the fact that the pre-emersion drying condition was more severe for the first wetting than the following ones. As a matter of fact, the mudstones prior to testing were oven-dried for 6 hours at a temperature of 105°C which corresponds to a much higher drying rate than the following ones. It can be deduced from this result that longer and more severe droughts before rainfall events could be more detrimental to slope stability.

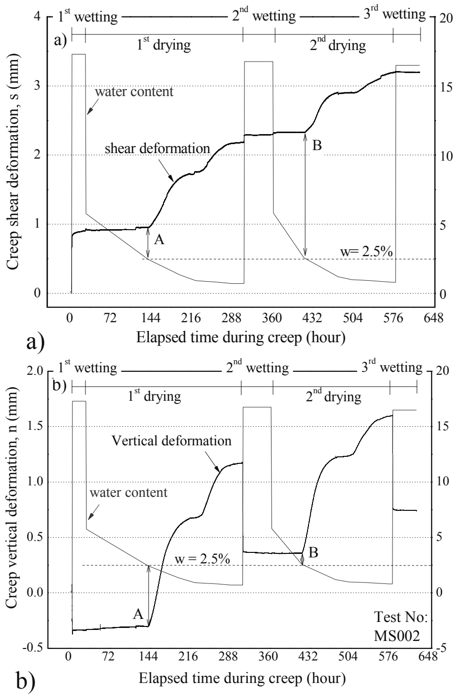

Fig. 7 Time histories of water content and creep deformation (a) Shear b) Vertical deformation) under cyclic wetting and drying for 3 times for R= 0.5

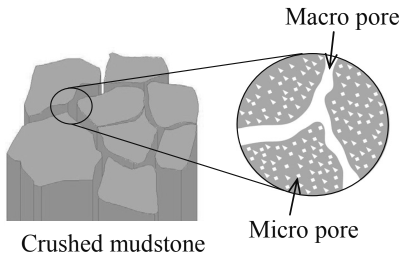

Fig. 8 Macro and micro pores system

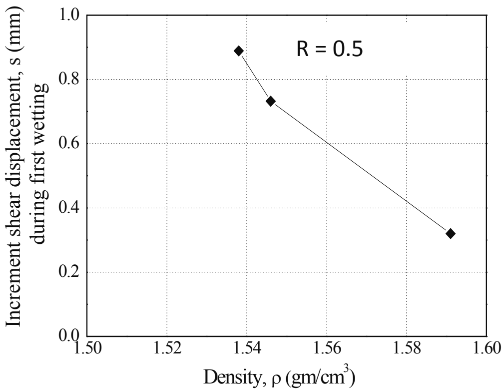

Fig. 9 Relationship between density of the specimen and increment shear displacement during first wetting

In addition, from Fig. 10 a), the creep shear deformation caused by wetting seems to be decreased with progress of wetting and drying cycle, almost zero during the third wetting, even the water content of specimen before wetting is relatively lower about 0.7 %. This may be attributed to the specimen densification due to previous wetting and drying processes (see Fig. 11). Figure 10 b) shows considerable vertical deformation that occurred in each wetting process. The vertical deformation in case of R= 0.3, however, is almost negligible except in the first wetting because of having higher water content (more than

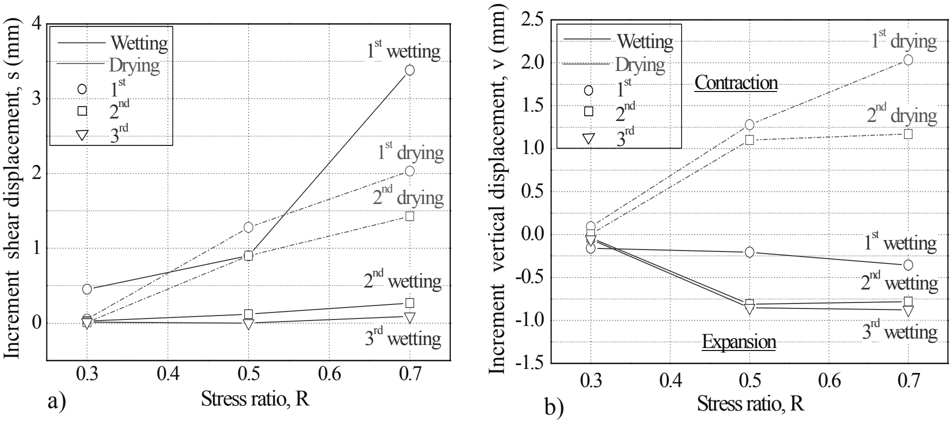

Fig. 10 Increment value of creep a) Shear b) Vertical displacement at each stress ratio, R

3 %) of specimen before the second and third wettings. The vertical deformation in the first wetting is affected by both R values during creep shear loading and the progress of wetting and drying cycles.

One of the noticeable behaviors observed in these experiments is a quite large creep deformation during the drying processes. As shown in Fig. 10 a), the creep shear deformation during drying increase with the increase in the stress ratio, R. However, in the case of sress ratio, R= 0.3, the lowest water content during the drying step is quite large (about 3 %). This may be reason for relatively small creep deformation during the drying process at stress ratio, R equal to 0.3. Reduction of pore water which lead to shrinkage and disaggregation of fabric especially around discontinuities during dry process. Consequently, such an evolution of soil grains produce rounded particles with relatively high sphericity and smooth circumference which sequentially decreases the interlocking behaviour (angle of internal friction) of granular medium (Moropoulou et al., 2004 and Aung et al., 2010). Similarly, particles slide on each other during shrinkage causing shear deformation. The strength and stiffness gained during drying process are opposing to the further increase in shear displacement with drainage and evaporation of pore water which lead to shrinkage and disaggregation of fabric especially around discontinuities. Therefore, the drying induced deformation of crushed mudstones is very complex which could be challenging and crucial importance for strategic geotechnical structures.

Figure 12 shows the shear deformation-volume change relationship for the three testing conditions under same stress conditions. All specimens under the three different testing condition exhibited dilative behavior during monotonic shear loading. However, it is seen that the residual state is no longer unique. In general, the position of residual state is unique under constant stress. The position of the residual state also varies with the degree of saturation (Kyokawa, 2011). Although, both the specimens with one time wetting and the one with three times wetting and drying history failed due to monotonic shear loading under fully saturated conditions, there is a considerable difference in the position of residual states probabaly because of particles crushing occurred during cyclic wetting and drying process.

The relationship between the stress ratio, R (= τ/σ_v) and shear displacement during monotonic loading is shown in Fig. 13. The specimen with one time wetting and the one with cyclic wetting and drying history exhibited largely different stress-displacement features from that of dry specimen. The peak shear strength of the saturated and cycle test samples are reduced by about 20 % as compared to the dry test.

Significant amount of particles are crushed due to immersion and cyclic wetting and drying. After experiment, it is found that about 1.5 % particles by mass become finer than 2.0 mm for the dry test, where as in the case of saturated and cyclic test 6.0 % and 9 % particles by mass become finer than 2.0 mm respectively. Similarly, the Degradation indexes were 0.067, 0.11 and 0.16 for dry, saturated and cyclic test. This results show higher value for the cyclic test due to repeated wetting and drying (see Fig. 14).

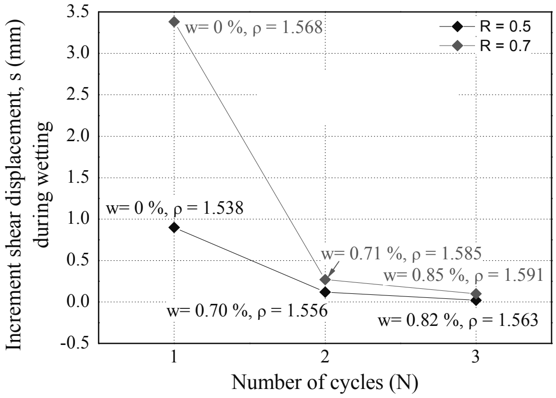

Fig. 11 Incremental creep shear displacement, s during wetting with increasing number of W/D

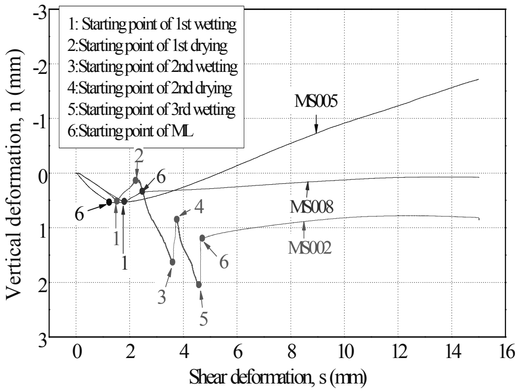

Fig. 12 Relation between shear deformation and vertical deformation for R = 0.5

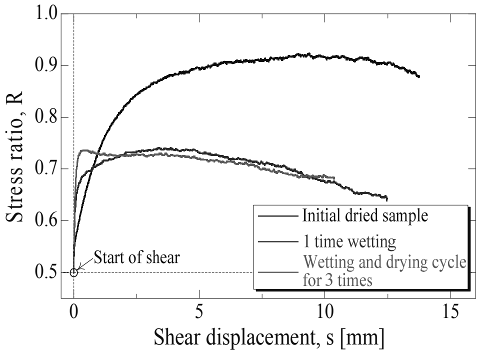

Fig. 13 R-*s* relationship under different test condition for R = 0.5

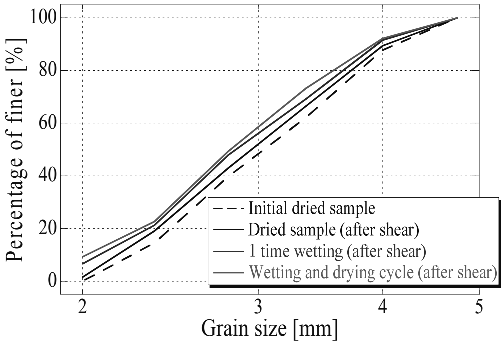

Fig. 14 Particle size distribution before and after experiment

Finally, one of the important finding of these experiments is a gradual decrease of the peak angle of friction with the increasing number of cycles as shown in Fig. 15. This may be attributed to particles crushing due slaking of crushed mudstone as described in previous paragraph. As already mentioned the slaking index and the slaking ratio of crushed mudstone used in this research are 1 and 96.86 which indicates the durable mudstones against slaking. So, the decrease of the peak angle of friction with the increase number of cycles is not significant for less number of wetting and drying cycles.

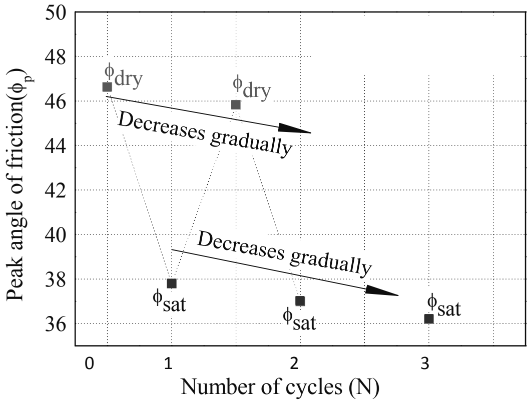

Fig. 15 Effect of cyclic wetting and drying on peak angle of friction (ϕ_p)

CONCLUSIONS

In order to investigate slaking effect on engineering behaviors of crushed mudstone, a series of direct shear tests were conducted. The following conclusions were obtained in this study.

A significant creep shear deformation could be found in the first wetting process. However, the amount of creep shear deformation during wetting is decreased with step of the drying and wetting cycles. Almost equal vertical deformation occurs in each wetting step if the water content of the specimen before wetting becomes quite smaller. Creep shear displacement during the wetting phase increases with a higher stress ratio, R which would indicate a higher slaking-induced instability at steeper slopes. Shear displacement during the first wetting phase is very large as compared to the second and third wetting. This could be explained by the fact that the pre-emersion drying condition was more severe for the 1st wetting than the following ones. As a matter of fact, the mudstones prior to testing were oven-dried for 6 hours at a temperature of 105°C which corresponds to a much higher drying rate than the following ones: longer and more severe droughts before rainfall events could be more detrimental to slope stability.

During the drying process, a significant creep deformation is found to occur when water content becomes less than 2.5 %. Creep deformation during drying is increased with the increase in stress ratio, R. A gradual decrease of the peak angle of friction is observed with the increasing number of cycles. Moreover, a 20% reduction in the peak shear strength for the cyclic wetting and drying was obtained compared to the dry condition test. Similarly, about 3 % more particles crushing of the mudstones samples after cyclic wetting and drying is found.

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