CONTRIBUTION OF MICRO STRUCTURE TO REPEATED LOADING EFFECT ON COMPACTED ALLOPHANEOUS VOLCANIC ASH SOIL

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ABSTRACT

The hardening effect and delay of propagation of pore water pressure were observed in repeated loading test on the specimens of compacted allophanaceous volcanic ash soils under undrained condition. These phenomena occurred even in the specimen whose degree of saturation was higher than 95%.

This research was carried out to investigate the mechanism of hardening effect of repeated loading on the above highly saturated specimens from the viewpoint on the relation between hardening effect and micro structure. Then, the following results were obtained. (1) The difference of micro structure influenced not only on the behavior of soil in the standard undrained triaxial compression test but also on that in the undrained repeated loading test. (2) Undrained repeated loading had both of hardening and softening effects. (3) The hardening effect was given by the gradual increase in contact area between soil particles, anisotropy and density resulted from deformation and fracture of soil peds and compression of residual micro air bubbles during repeated loading. (4) To obtain the yielding repeated load ratio, the strain ratio (recoverable strain/irrecoverable strain) method was more favorable for allophanaceous volcanic ash soils than the strain rate method. The yielding repeated load ratio was 0.4 through all kinds of specimens used in this research.

Key words : cohesive volcanic ash soil, consolidated undrained compression test, pore pressure, repeated load, soil structure, stress-strain curve (IGC : D 7/D 6)

INTRODUCTION

Kuroboku (organic cohesive volcanic ash soil) and Akaboku (inorganic cohesive volcanic ash soil) are typical allophanaceous volcanic ash soils which have high natural water

content. These soils compacted at high water contents have very low permeability (Tokunaga, 1968). The repeated loading effect on these compacted soils sheared under undrained condition has been studied by many research workers (Kitazono and Suzuki,

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Table 1. Physical characteristics of samples

	Akaboku	Kuroboku
W_n (%)	107	208
G_s	2.86	2.66
W_l (%)	123	210
W_p (%)	83	162
I_p	40	48

1979; Kitazono, Suzuki and Aramaki, 1985), and the following results have been obtained. (1) These compacted soils have yield points in repeated loading, and the yield points are 40~60% of static strength in undrained triaxial compression test. (2) In Akaboku, some increase in the modulus of deformation (hardening effect) was recognized after repeated loading, but not in Kuroboku. (3) The hardening effect of stage repeated loading is larger than that of the stretch repeated loading (Kitazono, Suzuki and Aramaki, 1985). (4) It is supposed that compression of small confined air bubbles in soil (increase in density of specimen) and change in micro structure are important factors for above hardening effect, but contribution of these factors to the effect has not yet explained reasonably well.

This study was intended to investigate the contribution of change in micro structure to hardening effect of repeated loading. In this study following new devices were introduced. 1) Both of remolded consolidated spec-

imens (R-specimen) and impact compacted specimens (I-specimen) were prepared to be compared in hardening effect. R-specimen has more homogeneous and more anisotropic soil structure than I-specimen (Suzuki and Kitazono, 1984). 2) Saturating operation, flushing (Shimizu, 1983) and back pressure, were given to specimens to remove the influence of increase in density due to compression of small entrapped air bubbles in specimens as much as possible. 3) The change in micro soil structure was confirmed by sieve analysis in the water and scanning electron microscope, and the effect of saturating operation was confirmed with the value of Skempton's coefficient of pore water pressure (B) more than 0.9.

SAMPLE AND SPECIMEN PREPARATION

Samples were inorganic cohesive volcanic ash soil (Akaboku) and organic cohesive volcanic ash soil (Kuroboku) which were taken at Ubuyama Village in Kumamoto Prefecture. Physical characteristics of these soils were shown in Table 1.

Preparation of Specimen

(1) Impact compacted specimens (I-specimen) were compacted in the mold, 50 mm in inner diameter and 125 mm in height, with the energy equivalent to that of impact compaction test of JIS-A 1210 T 1979 at

Table 2. Fundamental properties of specimens

		I-specimen		R-specimen	
		Akaboku	Kuroboku	Akaboku	Kuroboku
Initial state	W_0 (%)	105	205	102	186
	ρ_{d0} (g/cm ³)	0.67	0.40	0.72	0.45
	e_0	3.30	5.73	3.02	4.94
	I_{e0}	0.45	0.10	0.53	0.50
	B_0	0.83	0.96	0.98	0.98
	B^*	0.92	0.98	0.98	0.98
State after consolidation	W (%)	102	187	85	156
	ρ_d (g/cm ³)	0.74	0.45	0.83	0.52
	e	2.89	4.91	2.43	4.14
	I_e	0.53	0.48	0.95	1.13
CU test	$(\sigma_1 - \sigma_3)f_0$ (kPa)	172.0	143.8	127.2	148.8
	$E_{50,0}$ (MPa)	4.51	9.11	12.1	21.8

* B value after surcharged back pressure

the natural moisture content.

(2) Remolded consolidated specimens (R-specimen) were prepared by one dimensional consolidation with the pressure of 49 kPa in a container (height : 300 mm, diameter : 450 mm) for a week which corresponds to the period of primary consolidation after remolding at the moisture content of about 20% higher than liquid limit. The moisture content of sample before remolding was $W_n=107\%$ in Akaboku or $W_n=208\%$ in Kuroboku. Specimens whose axial direction agreed with consolidation direction were cut out from these consolidated samples and formed to cylinders of 50 mm in diameter and 125 mm in height.

Consequently, four groups of specimens shown in Table 2 were prepared.

PROCEDURE OF EXPERIMENT

(1) The Operation of Saturating Specimen

Initially the value of coefficient of pore water pressure (B) of R-specimen was not less than 0.95 and that of I-specimen was nearly equal to 0.8. However, after being subjected to flushing and surcharge of back pressure (98 kPa, for more than twenty hours) the value of coefficient of the I-specimen was more than 0.92 and that of R-specimen was nearly 0.98. The above result ($B<1.00$) showed that the specimens were still not perfectly saturated and held micro air bubbles confined within peds of allophane and organic matter of themselves.

(2) Sieve Analysis in the Water

The sieve analysis in the water was taken in order to observe the difference in grain size distribution among R-specimen, I-specimen and both ones subjected to repeated loading. The specimen broken to small pieces of about 1 cm^3 was submerged for one day and sieved by sieves larger than $74\text{ }\mu\text{m}$ in the under water. The above wet method for grain size distribution analysis is taken to get ped size distribution for wet sample. In sieve analysis in the water a sample was washed five times on each sieve

(for about 30 seconds per washing). Five times of washing was applied five because the water became almost clean after five times sieving.

(3) Observation by Electron Microscope Photograph

The scanning electron microscope photograph of micro soil structure was taken to visually observe the micro-structure of I-specimen and R-specimen. The specimen for electron microscope observation was cut from specimen for triaxial compression test in cube of 1 cm^3 . The specimen was divided into two pieces by hand without a cutting knife not to disturbed the cutting surfaces, and one of these surfaces was observed. After dried in an oven for 24 hours, the sample was trimmed for observation.

(4) Undrained Triaxial Compression Test and Undrained Repeated Loading Test (Table 3)

After the back pressure were surcharged, all specimens were isotropically consolidated at a pressure of 98 kPa for 24 hours to be in normally consolidated state at the initial stress condition.

Next, the ordinary undrained triaxial compression test (strain rate : $\dot{\epsilon}=1\%/min$ (cf. appendix)) (CU test) was preformed on some specimens of each specimen group in Table 2 to get the fundamental data to evaluate the repeated loading effect. Undrained repeated loading test was performed on the other specimens at a confining pressure of 98 kPa. Repeated loads level of which was shown in terms of load ratio (R_L) to compression strength in CU test ($(\sigma_1-\sigma_3)_{f0}$) were loaded

Table 3. Kinds of triaxial compression test

	Akaboku	Kuroboku
I-specimen	CU test $(\sigma_1-\sigma_3)_{f0}, E_{50,0}$	CU test $(\sigma_1-\sigma_3)_{f0}, E_{50,0}$
	Rep-U test $(\sigma_1-\sigma_3)_f, E_{50}$	Rep-U test $(\sigma_1-\sigma_3)_f, E_{50}$
R-specimen	CU test $(\sigma_1-\sigma_3)_{f0}, E_{50,0}$	CU test $(\sigma_1-\sigma_3)_{f0}, E_{50,0}$
	Rep-U test $(\sigma_1-\sigma_3)_f, E_{50}$	Rep-U test $(\sigma_1-\sigma_3)_f, E_{50}$

in rectangular waves with 1 Hz. Details of these tests were written in the previous report (Kitazono and Suzuki, 1979 ; Kitazono, Suzuki and Aramaki, 1985).

An undrained triaxial compression test was carried out on the specimen after repeated loading (Rep-U test) and repeated loading effect on modulus of deformation (E_{50}) and compression strength ($(\sigma_1 - \sigma_3)_f$) was investigated.

THE DIFFERENCE OF MICRO SOIL STRUCTURE FORMED BY COMPACTED METHODS

The following difference of micro soil structure in the specimen groups in Table 2 were found from results of the in-water sieving test, electron microscope photograph observation.

1) From Fig.1 which shows grain size distribution curves of the fraction coarser than silt of I-specimen and R-specimen it is found that I-specimen is more abundant in large peds than R-specimen. Therefore, it was supposed that there were differences of stress transmission and deformation in soil structure between I-specimen and R-specimen. Moreover, curves with Δ and ∇ are grain size distribution curves of I-specimen after repeated loading, which show that peds are broken to smaller ones by repeated loading.

From electron microscope photograph, the following difference between I-specimen and R-specimen were recognized. Here, Photo. 1 and Photo. 2 were electron microscope photographs of I-specimen and R-specimen each

Fig. 1. Grain size distribution curve with sieve analysis in the water

of Akaboku, in which large pores shown in Photo.2 are supposed to be shrinkage crack due to drying.

2) In the case of I-specimen, soil structure was less homogeneous and abundant in larger pores than in the case of R-specimen which was subjected to enough remolding and the virtual pre-consolidation to fracture large peds.

(3) Also, from details of specimens shown in Table 2, decrease in moisture content of R-specimen after isotropic consolidation was more remarkable than that of I-specimens.

(4) Moreover, mechanical anisotropy (Kazama, Yoshinaka and Kubojima, 1973 ; Matsuo, Kamon, Matsushita and Fukuda, 1978) was supposed to grow in R-specimen because of the virtual pre-consolidation after remolding.

From these results it was assumed that R-specimen had the stiffness and the brittleness higher than I-specimen for axial loading, and the yield zone will grow more rapidly in R-specimen than in I-specimen under the load higher than the yield load.

5) Comparing Akaboku and Kuroboku after isotropic consolidation (Table 2), the consistency index (I_c) of I-specimen of Akaboku was higher than that of Kuroboku but it was converse for R-specimen.

From the above results, the following was understood. The natural soil structure of Akaboku keeps high stability for the floc-

Photo. 1. Electron microscope photograph of I-specimen on Akaboku

Photo. 2. Electron microscope photograph of R-specimen on Akaboku

culence structure and the cementation. Then, I-specimen still had some large stable peds (Photo.1) but R-specimen which was sufficiently remolded almost lost large stable peds and had homogeneous structure (Photo. 2). When large peds fractured, the quasi-confined water in large peds was released to the free water (Yasutomi and Takenaka, 1970). Accordingly, the rate of change from the quasi-confined water to the free water was more in remolded soil than in impact compacted soil (Suzuki, 1972). This appeared to cause the difference of moisture content after isotropic consolidation ($\sigma_c = 98$ kPa) as shown in Table 2.

On the other hand, Kuroboku keeps much more confined water and quasi-confined water due to much organic matters (Suzuki, 1972). Then bonding force between soil particles of Kuroboku was weaker than that

of Akaboku. Therefore, the fracture of large peds a impact and remolding on Kuroboku was more progressive than that on Akaboku. Particularly, the difference in fracture of large peds between both soils was remarkable in I-specimen. The difference of consistency index of R-specimen after consolidation was considered to result in ped fracture with above change of water.

The above difference of soil structure between the specimens gave the following influence on the behavior of deformation at CU test (Fig. 2).

1) Comparing the $(\sigma_1 - \sigma_3) - \epsilon$ curve of I-specimen with that of R-specimen, the initial resistance of R-specimen was larger than that of I-specimen and the yield point of R-specimen was more definable than that of I-specimen in both of Akaboku and Kuroboku.

2) Comparing the $(\sigma_1 - \sigma_3) - \epsilon$ curve of I-specimen of Akaboku with that of Kuroboku, I-specimen of Akaboku showed the yield point less undefinable than that of Kuroboku.

3) Comparing the $(\sigma_1 - \sigma_3) - \epsilon$ curve of R-specimen of Akaboku with that of Kuroboku, R-specimen of Akaboku showed much more decrease in strength by remolding than that of Kuroboku.

UNDRAINED REPEATED LOADING TEST

The Deformation Under Repeated Loading

The relationship of the axial strain(ϵ) with the number of cycles(N) in repeated loading test is shown in Fig.3. Fig.4 shows the relationship of strain rate($\dot{\epsilon}$) with load ratio (R_L). The strain rate was defined by the following expression for the stage of loading with cycle number of $N=100 \sim 200$ where the strain was almost linear against logarithm of number of cycles. Fig.5 shows the relationship of strain ratio (recoverable strain (ϵ_r)/irrecoverable strain (ϵ_p)) with R_L at 100 th cycle of loading ($N=100$) which was beginning of the above cycle range.

Here,

Fig. 2. Stress-strain behavior in isotropic consolidated undrained triaxial compression test (CU test)

Fig. 3. Axial strain in repeated loading

Fig. 4. Strain rate against load ratio in repeated loading ($N=10^2 \sim 2 \times 10^2$)

$$\varepsilon = \varepsilon_r + \varepsilon_p$$

$$\dot{\varepsilon} = \frac{\Delta \varepsilon_i}{\Delta t_i} = \frac{\varepsilon(N=2 \times 10^2) - \varepsilon(N=10^2)}{10^2(\text{s})}$$

ε : total strain (axial strain at loading)

ε_r : recoverable strain during repeated loading

ε_p : irrecoverable strain during repeated loading

$\dot{\varepsilon}$: strain rate

$\Delta \varepsilon_i$: total strain increment during loading from $N=10^2$ to $N=2 \times 10^2$

Δt_i : loading time from $N=10^2$ to $N=2 \times 10^2$ ($\Delta t_i = 10^2 \text{ s}$)

Each curve in Fig. 3 shows tendency that ε increases suddenly with R_L for the range of $R_L > 0.4$, and this tendency is more remarkable in R-specimen than I-specimen.

Fig. 5. Strain ratio (recoverable strain/irrecoverable strain) in repeated loading ($N=10^2$)

Strain of R-specimen is smaller than that of I-specimen during early stage of loading ($N < 10^2$), and strain in R-specimen increased suddenly at $N=10^2$. These difference between I-specimen and R-specimen are caused by the difference of soil structure between both kinds of specimen as mentioned previously. The axial strain in I-specimen progressed gradually with deformation and fracture of large peds in certain shear zones getting homogeneity and anisotropy from the early stage of loading. The axial strain in R-specimen which was homogeneous and anisotropic was small during the early stage of loading but progressed more rapidly after few ten time's loading with sudden increase in strain developed in certain shear zones.

In Fig. 4, the yield load ratio (R_{Ly} , Kitazono and Suzuki, 1979) either of I-specimen or R-specimen was nearly 0.4 of Akaboku, which was a little smaller than that of I-specimen (0.6) or R-specimen (0.5) of Kuroboku. Moreover, R-specimen shows the distinct yielding compared with I-specimen as assumed from difference of soil structure between both specimens.

Also, a peak of ratio, $\varepsilon_r/\varepsilon_p$, was observed at $R_L=0.4$ in each curve in Fig. 5. Recoverable and irrecoverable strain increased

with increase of load ratio. Ratio $\varepsilon_r/\varepsilon_p$ was, however, increased because the rate of increase in recoverable strain was larger than that in irrecoverable strain for small load ratio. When soil structure yielded, irrecoverable strain more rapidly increased than recoverable strain, and then $\varepsilon_r/\varepsilon_p$ decreased. That is to say, decrease in $\varepsilon_r/\varepsilon_p$ indicated the yielding of the soil structure, and the yield load ratio can be regarded as the load ratio at peak of $\varepsilon_r/\varepsilon_p$. Adopting to this method, R_{Ly} (yield load ratio) was about 0.4 through all specimen as shown in Fig. 5. Thus, the difference of values of yield load ratio between the two methods (Fig. 4 and Fig. 5) were recognized. This difference will be discussed later in this paper.

Comparing I-specimen with R-specimen in Fig. 5 the following differences are recognized. (1) The rate of increase in $\varepsilon_r/\varepsilon_p$ with $R_L(<R_{Ly})$ was higher in R-specimen than in I-specimen. (2) The rate of decrease in $\varepsilon_r/\varepsilon_p$, the growth of yield zone, against $R_L(>R_{Ly})$ was higher in R-specimen than in I-specimen. It is considered that the above difference of repeated loading effect between both kinds of specimens was certainly attributed to the structural difference between these specimens as mentioned already. Especially in repeated loading of R_L smaller than R_{Ly} , homogeneity and anisotropy of soil structure grew gradually with crush (Fig. 1) and orientation of peds, and stiffness increased against axial load in I-specimen but these changes of soil structure slightly occurred in R-specimen. This is hardening ef-

fect of repeated loading on I-specimen. Softening effect for $R_L(>R_{Ly})$ was lower on I-specimen than on R-specimen because yielding in I-specimen did not occur so rapidly as in R-specimen. From above investigation, contribution of soil structure to repeated loading effect on I-specimen were understood. Comparing Akaboku with Kuroboku, the $\varepsilon_r/\varepsilon_p$ of Kuroboku was much higher, because organic matter might give more elastic soil structure.

The Behavior of Pore Water Pressure

Behavior of pore water pressure (u) during repeated loading is shown in Fig. 6, in which following two points were distinctive.

1) Pore water pressure increased with the number of repeated loading but the increasing rate decreased against the number of repeated loading for a constant load through all specimens.

2) Comparing I-specimen and R-specimen, rise of pore water pressure in R-specimen was slower than that in I-specimen and showed the highest rate around $N=10^2$.

In the above behavior, the first one was the reflection of dilatancy in normally consolidated soils, and the second one was the reflection of structural difference between both kinds of specimens as mentioned previously.

In this investigation, delay in rising of pore water pressure was hardly observed because operation for saturation was given to specimens.

Fig. 6. Pore water pressure in repeated loading

THE EFFECT OF UNDRAINED REPEATED PRELOADING ON REP-U TEST

The stress-strain curves of Rep-U test of specimen after repeated loading test are shown in Fig. 7 and Fig. 8. The mark(●) linked to each curve with broken line in the figure shows the state at the end of repeated loading. A dot-dash curve shows the stress-strain relation of standard CU test (strain rate was 1%/min).

Loading curves, both of I-specimen or R-specimen, almost agreed with the unloading curves from the state at the end of repeated

Fig. 7. Stress-strain behavior in undrained triaxial compression test of I-specimen after repeated loading (Rep-U test)

Fig. 8. Stress-strain behavior in undrained triaxial compression test of R-specimen after repeated loading (Rep-U test)

Fig. 9. Pore water pressure-strain behavior in undrained triaxial compression test of I-specimen after repeated loading (Rep-U test)

loading, and showed yielding along the stress-strain curve of CU test. However, the loading curves of specimens preloaded by repeating load in the range, $R_L > R_{Ly}$, looked unstable because they have a few deflection points on themselves. These phenomena indicated the following effect of repeated preloading on the behavior in Rep-U test.

1) Repeated loading in the range, $R_L < R_{Ly}$, increased elasticity and stiffness of the specimen (hardening effect), and this effect was especially remarkable in I-specimen.

2) Repeated loading in the range, $R_L > R_{Ly}$, made specimens yield gradually keeping metastable state (Mitchell, 1976) while the strain controlled Rep-U test made specimens yield suddenly.

3) The above hardening effect vanished when the strain increased beyond 3% in Rep-U test.

Fig. 9 shows the relation between pore water pressure(u) and axial strain(ϵ) during Rep-U test on I-specimen preloaded with repeated load (Rep-U test). Points shown by marks(•) in the figure represented the state of specimens at the end repeated loading. The u - ϵ curves of Rep-U test on specimens preloaded with repeated load in the range, $R_L < R_{Ly}$, almost followed the point representing the state at the end of repeated loading. In cases of Rep-U tests on specimens preloaded with repeated load in the range, $R \geq 0.4$, however, pore water pressure showed higher value than that of the corresponding point representing the state at the end repeated loading, and after the peak over the point, decreased gradually to get close to the curve in the CU test (dot-dash curve). These difference of the pore water pressure between values at peak of the curve and the point(•) represented the residual pore water pressure in inner part of specimens at the metastable state. Decrease in the pore water pressure after the peak showed dissipation of the residual pore water pressure with the stress condition close to the critical state. It is assumed that this residual pore water pressure made the

Fig. 10. Effect of repeated loading on modulus of deformation and compressive strength on Akaboku

Fig. 11. Effect of repeated loading on modulus of deformation and compressive strength on Kuroboku

previous stress-strain curve at Rep-U test on specimens preloaded with repeated load, $R_L \geq 0.4$, unstable. This residual pore water pressure was a part of pore water pressure risen in the specimen partially yielded during repeated preloading in the range, $R_L > R_{Ly}$ as previous mentioned (cf. Fig. 6).

Fig. 10 and Fig. 11 show the effect of repeated loading on compressive strength $((\sigma_1 - \sigma_3)_f)$ and modulus of deformation (E_{50}) in Rep-U test in terms of strength ratio and stiffness ratio which are the ratio of strength and the modulus of deformation at Rep-U test to each one in CU test $((\sigma_1 - \sigma_3)_{f0}$ or $E_{50,0}$).

In Fig. 10, the repeated loading effect on compressive strength of either I-specimen or R-specimen hardly appeared in Akaboku as known already, (cf. Fig. 7 or Fig. 8, Seed, McNeill and Guein, 1958). The hardening effect of repeated loading appeared on the modulus of deformation of all of I-specimens. The stiffness ratio of I-specimens showed peak value of about 3.5 at $0.4 (= R_{Ly})$. On the other hand, the hardening effect on modulus of deformation of R-specimen was not much even in the range of $R_L < R_{Ly} (= 0.4)$ except the peak value, about 1.4, at $R_L = R_{Ly}$. The softening effect on R-specimen rather appeared in the range of $R_L > R_{Ly}$.

In case of Kuroboku (Fig. 11), the repeated loading effect on strength and modulus of deformation of either I-specimen or R-specimen showed the tendency almost same to that in case of Akaboku. The hardening effect on modulus of deformation of I-specimen, however, showed the peak value (of about 2), at $R_L = 0.3 \sim 0.4$, which was about 60% of the peak value in the case of Akaboku. Here, in Kuroboku, the yielding load ratio (R_{Ly}) obtained from $\dot{\epsilon} - R_L$ relation was 0.6 for I-specimen or 0.5 for R-specimen but that obtained from $\epsilon_r/\epsilon_p - R_L$ relation was 0.4 through I-specimen and R-specimen as described in the preceding section. Comparing these yielding load ratios obtained by two kinds of methods with repeated loading effect on modulus of deformation shown in Fig. 11, it was found that the yielding load ratio obtained by $\epsilon_r/\epsilon_p - R_L$ method was better than that obtained by $\dot{\epsilon} - R_L$ method because ϵ_r/ϵ_p was sensitive to change in soil structure than $\dot{\epsilon}$, and $\epsilon_r/\epsilon_p - R_L$ method gave safer side value than $\dot{\epsilon} - R_L$ method. The reason that the difference between yield load ratios obtained from $\dot{\epsilon} - R_L$ relation and from $\epsilon_r/\epsilon_p - R_L$ relation appeared in Kuroboku is assumed as the following. In case of Kuroboku, the micro structure was rich in elasticity due to organic matter. The ratio of irrecoverable strain to the total strain in Kuroboku was considerably small compared with that in Akaboku, and then increase in irrecoverable strain due to yield did not

appeared so sensitively in $\dot{\epsilon}$ as in ϵ_r/ϵ_p . From the above, $\epsilon_r/\epsilon_p - R_L$ method was found to be more useful in obtaining the yielding repeated load ratio rather than $\dot{\epsilon} - R_L$ method.

It is interesting that the yielding repeated load ratio obtained with $\epsilon_r/\epsilon_p - R_L$ method was 0.4 through both kinds of allophanous volcanic ash soils, Akaboku and Kuroboku.

CONCLUSION

A summary of the results of this study were as follows.

(1) The soil structure of impact compacted specimen was rich in flocculent large peds which had micro air bubbles in themselves and inhomogeneous, but that of remolded consolidated specimen consisted of fractured smaller peds uniform in their size and was denser, more homogeneous and more anisotropic. The difference of soil structure between both kind of specimens influenced not only on the behavior at standard undrained triaxial compression test but also on the effect of repeated loading.

(2) Undrained repeated loading had hardening and softening effects. The first one appeared remarkably on I-specimen but the second one appeared remarkably on R-specimen.

(3) The hardening effect was caused by increase in density and anisotropy resulted from gradual deformation and fracture of soil peds during repeated loading.

(4) The softening effect was assumed to be a phenomenon on the process of structural yield in some zone while the hardening effect which might be considered as a phenomenon in the process of yield of peds as mentioned in (3).

(5) On Kuroboku which had a lot of organic matter on surface of soil particles, neither hardening nor softening effect was remarkable compared with on Akaboku because the organic matter weakened bonding force among soil particles but riched elastics.

(6) To obtain yielding repeated load ratio, the $\epsilon_r/\epsilon_p - R_L$ method was more favorable

for allophanous volcanic ash soils than $\dot{\epsilon} - R_L$ method. The yielding repeated load ratio was 0.4 through all kinds of specimens used in this research.

From above conclusion, mechanism of repeated loading effect was explained. If this result is applied to subgrade of a road on fill of allophanous volcanic ash soils, stability of the subgrade will be expected to gain by traffic loads controlled under the yielding repeated load.

NOTATIONS

- B = coefficient of pore water pressure
 CU test = consolidated undrained triaxial compression test
 E_{50} = modulus of deformation in Rep-U test
 $E_{50,0}$ = modulus of deformation in CU test
 I_c = consistency index
 I-specimen = impact-compacted specimen
 N = number of cycles
 Rep-U test = undrained triaxial compression test after repeated loading
 R_L = load ratio
 R_{Ly} = yield load ratio
 R-specimen = remolded-consolidated specimen
 ϵ = total strain (axial strain)
 ϵ_r = recoverable strain during repeated loading
 ϵ_p = irrecoverable strain during repeated loading
 $\dot{\epsilon}$ = strain rate
 σ_c = confining pressure
 $(\sigma_1 - \sigma_3)_f$ = compression strength in Rep-U test
 $(\sigma_1 - \sigma_3)_{f0}$ = compression strength in CU test

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not sufficiently developed at the strain rate ($\dot{\epsilon}$) of 1%/min in triaxial compression test. Therefore, the relationship between strain and pore water pressure at the different strain rate is shown in Fig. A-1 on Akaboku. In the figure, pore water pressure were presented in terms of the ratio to the one at the strain rate of 1%/min. The followings were found. In I-specimen, the difference of pore water pressure depending on the strain rate was almost negligible. In R-specimen, however, the pore water pressure at the strain rate of 0.06%/min was about 20% higher than at that of 1%/min at $\epsilon = 1\%$ and about 10% higher than at that of 1%/min for strain larger than 2% ($\epsilon > 2\%$). This difference of pore water pressure depending on strain rate may not be important to explain behavior of specimen subjected to repeated loading (cf. Fig. 9).

Fig. A-1. Effect of strain rate on pore water pressure in undrained triaxial compression test

APPENDIX

It is said that the pore water pressure does