

# STRENGTH AND DEFORMATION CHARACTERISTICS OF ARTIFICIAL LIGHTWEIGHT SUBBASE MATERIAL UNDER MONOTONIC AND CYCLIC LOADING

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As roads often have a residual settlement on soft foundations, reducing the weight of the subbase course is an alternative way to solve this problem. In this study, the strength and deformation characteristics of artificial lightweight subbase course material under monotonic and cyclic loading were discussed. The specimens in the dry and optimum moisture content condition were applied cyclic loading by 10,000 cycles under three confining pressures (29.4, 49.0, and 68.6 kPa), and then the effects of cyclic loading on the strength and deformation were discussed. From the test results, it was found that the shear strength of the specimens after cyclic loading decreased in the dry condition, while the shear strength of the specimens after cyclic loading was basically unchanged in the optimum moisture content condition. And it is considered that the deformation modulus of specimens after cyclic loading increased in both conditions.

**Key Words :** *subbase course material, cyclic loading, triaxial test, strength, deformation*

## 1. INTRODUCTION

In recent years, as the aging of the infrastructure such as bridge and road has progressed, there is the case that the settlement of the transition zones between the bridge deck and road embankments on soft soils arises. It is a common problem of the world that the differential settlement between the bridge abutment and embankment leads to difference in level on both sides of the bridge structure, especially bridges were built on soft soil. Hopkins and Deen investigated and reported that 78 % of the approach bridges of hundreds of highway bridges in Kentucky need some form of maintenance to alleviate the concave-convex problem on both sides of the bridge deck <sup>1)</sup>. Besides the bumpy problem of the bridge abutment and road embankments<sup>2)-6)</sup>, there is a more common road problem of the world, which is the uneven settlement of the road built on soft ground with long-term vehicle loading, resulting in potholes.

To solve the above two road problems and ensure

the normal use of these infrastructures, it is necessary to repair and pave again. The usual repair method is to excavate the road surface, and the overlay is executed. For roads to excessive traffic and roads where there is only partial settlement, the reduction methods for influence of re-paving on the normal traffic of the road and the time on re-paving will not be excavation of the damaged road surface but directly re-paving the road. However, for some roads built on soft ground, the weight load on the road foundation will also increase as the pavement will be thicker by repair. In this way, the repeated repair and paving of the same road will not only make the road unable to pass normally but also the repair and maintenance costs that need to be spent is increasing<sup>4),5),7)</sup>. From these situations, it is important that the upper load of the road foundation to avoid road residual settlement is reduced.

In this study, in order to reduce the residual settlement of the road and the bridge approach on the soft soil foundation by reducing the weight of the subbase

course, a new lightweight subbase course material is used to replace the common subbase course material. A series of monotonic and cyclic triaxial tests were conducted to investigate the strength and deformation characteristics of the lightweight subbase course materials, and the experimental results were used to check whether the lightweight materials can be used for the subbase course of the road.

## 2. SPECIMEN PREPARATION AND TEST PROCEDURE

### (1) Test material

In this study, an artificial lightweight material<sup>8)</sup> widely used in Japan is used as fill material, which is made by firing and foaming expanded shale at high temperatures, and the soil particle density is 1.958 g/cm<sup>3</sup>. Because the particle gradation of a single coarse aggregate is not good and it is difficult to be compacted during use, another type of fine aggregate is used in combination with it. Since this study is a basic study to investigate the mechanical property of artificial lightweight subbase course material, a cement standard sand<sup>9)</sup> was selected as another type of aggregate easy to get, and the soil particle density is 2.650 g/cm<sup>3</sup>. The two materials are mixed in a mass ratio of 1:1 under the dry condition. The volumetric weight of the common subbase material is 20.0 kN/m<sup>3</sup>, and the lightweight subbase material in this study is 17.0 kN/m<sup>3</sup>. It is 85 % of the weight of the common subbase material<sup>10)</sup>.

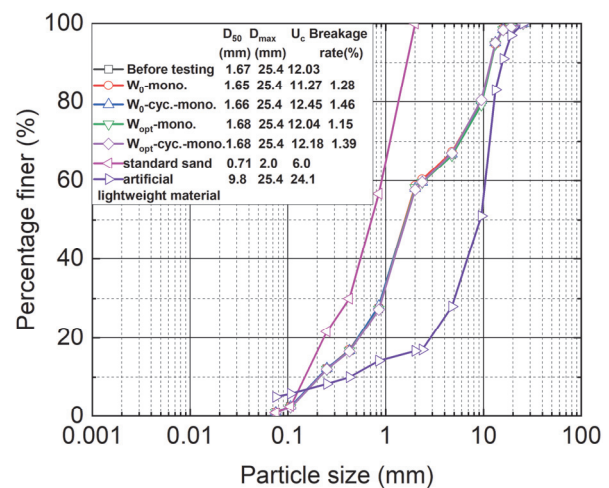
**Fig.1** shows the particle sizes distribution curves of the materials, it was found that the mixed materials before and after the test are almost same. According to the method of Marsal<sup>11)</sup>, the breakage rate of the testing materials was calculated, and it was found that the breakage rate was about 1.3 % after each testing.

**Fig.2** shows the compaction curve of the mixed materials by the A-b method of the proctor compaction test of the Japanese Industrial Standards<sup>12)</sup>. It can be seen that the maximum dry density is 1.437 g/cm<sup>3</sup>, and the optimum moisture content is 9.38 %.

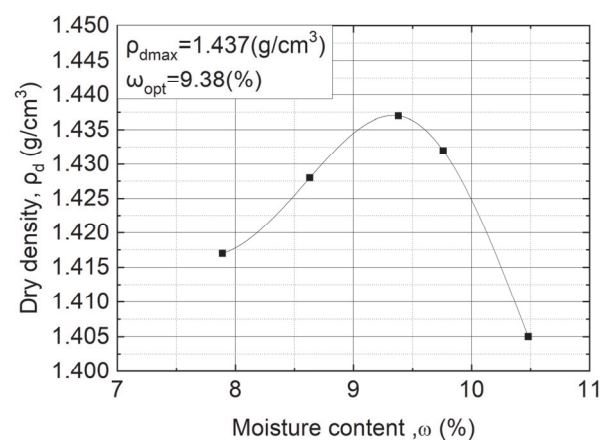
### (2) Specimen preparation

A medium-scale triaxial test apparatus is employed to research the strength and deformation of testing materials. Because the size of the specimens should be no less than 5 times the maximum particle size<sup>13),14)</sup>, the test specimens of this study have a diameter of 150 mm and a height of 360 mm.

The specimen is compacted by a top-loaded surface vibrator. The weight of the vibrator is 40 kN, and the vibration frequency by controllers is adjusted 100 Hz. Each specimen is loaded with seven layers. The compaction time of the first six layers is 10 min, and



**Fig.1** Grain-size distribution of testing materials.



**Fig.2** Compaction test curves of the testing materials.

that of the last layer is 5 min, because it will give the best compaction effect on the test specimens by the top-loaded surface vibrator. Before placing the material for the next layer, the surface of the previously compacted layer was scraped by a depth of about 2 cm to ensure good interlocking between the vertically adjacent layers<sup>15)-17)</sup>. After the specimens are made, it is ready for the triaxial test that an isotropic confining pressure is consolidated to the specimens for 16 hours.

**Table 1** shows the initial conditions of all specimens in this study. In this study, the different initial conditions are changed to analyze the effects of cyclic loading and water content on the strength and stiffness of the lightweight subbase course material. Under the optimum moisture content, it was found that the dry density obtained by vibrating compaction is less than that of the proctor compaction test. Generally, a dry density for compaction curve of soil under a constant energy decreases when a water content is decreased from optimum moisture content. However, for a cohesionless soil like sand, a minimum dry density is taken at some water content so that a dense state of soil particle is resisted due to the capillary tension of the pore water. This phenomenon is known as the bulking

**Table 1** Initial conditions of specimen

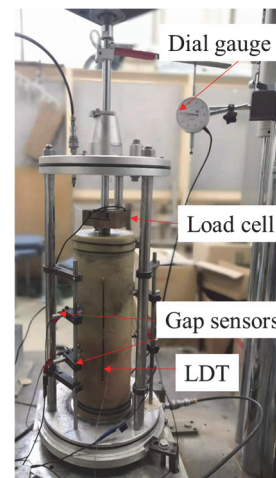
Specimen material state	Design moisture content (%)	Cyclic loading	Symbol	Confining pressure (kPa)	Dry density $\rho_d(\text{g/cm}^3)$
Dry condition ( $W_0$ )	0	without	$W_{0\text{-mono}}$	29.4	1.431
				49	1.452
				68.6	1.461
		with	$W_{0\text{-cyc-mono}}$	29.4	1.462
				49	1.475
				68.6	1.458
Optimum moisture content ( $W_{\text{opt}}$ )	9.38	without	$W_{\text{opt-mono}}$	29.4	1.356
				49	1.362
				68.6	1.359
		with	$W_{\text{opt-cyc-mono}}$	29.4	1.361
				49	1.365
				68.6	1.363

of sand<sup>18),19)</sup>. And more, when a water content is decreased, the capillary tension of the pore water becomes weak, soil particles come close. Consequently, a dry density increases again. Thus, a dry density at  $w=0\%$  indicates the relatively large value. It is considered that this tendency becomes more remarkable for a vibrating compaction. Therefore, it is considered that the dry density of a specimen with the dry condition ( $w=0\%$ ) is greater than the case of a wet specimen compacted by a vibrator in this study. On the other hand, the dry density of optimum moisture content in Table.1 is smaller than that in Fig.2. This is considered that the compaction energy by the vibrator with the optimum moisture content is smaller than that by a rammer.

### (3) Testing apparatus and procedure

**Fig.3** shows the medium-sized triaxial test apparatus used in this study. The apparatus equipped with a hydraulic servo control system by the feedback control method so that it can apply a high precision axial load to the specimen by stress control method and strain control method. Considering that the upper and lower sides of the specimen are covered with a layer of filter paper, the compression of the filter paper may cause bedding errors<sup>17),20)</sup>, in order to accurately get the data of the axial strain, Local Deformation Transducer (LDT)<sup>21)</sup> for measurement is used. Because of the limited measurement range of LDT, only 2 % of the change in the axial strain of the specimen can be measured, so the axial strain beyond the measurement range of LDT is supplemented by a dial gauge. To facilitate the acquisition of lateral strain and volume strain, two sets of proximeters are used in this test to measure.

In this study, all monotonic triaxial tests were conducted under the exhaust and drainage conditions at a constant rate of 0.18 mm/min. 12 sets of tests were conducted to consider the effect of pre-straining on the strength and deformation of specimens in two

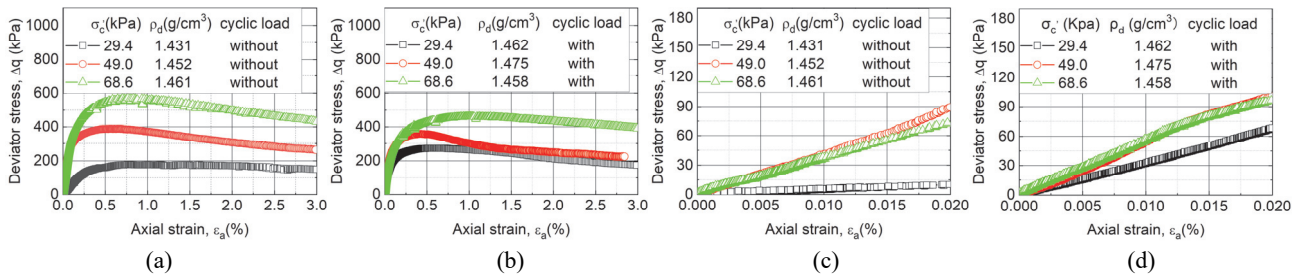
**Fig.3** Displacement measuring devices of triaxial apparatus

states (the dry and optimum moisture content condition) under different confining pressures (29.4, 49, and 68.6 kPa). To make the specimen with pre-straining, 10,000 cycles of vertical loading at a frequency of 0.125 Hz were performed for the specimen, where the vertical stress was changed between  $49.4 \pm 10$  kPa in a sinusoidal wave.

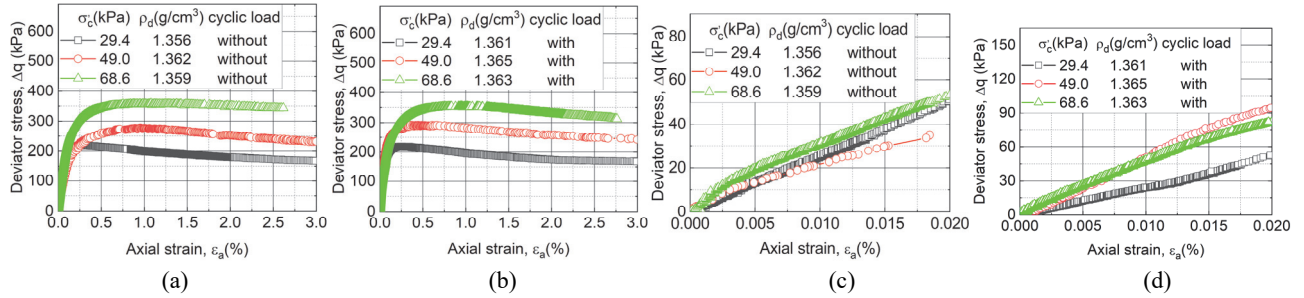
## 3. RESULTS AND DISCUSSIONS

### (1) Relationship between deviator stress and axial strain

**Fig.4, 5 (a), (b)** show that the deviator stress and axial strain relations of all test case in this study. It is seen that the stress reduces with increasing of strain in these stress-strain curves after the peak. This behavior is typical of dense granular materials and is commonly characterized as strain softening<sup>22),23)</sup>. The strain-softening process is concomitant with the generation of large deformations, which causes geometrically nonlinear effects to become important. When



**Fig.4** The stress-strain behavior of the specimens under the dry condition, (a) without cyclic loading, (b) with cyclic loading (c) without cyclic loading,  $\epsilon_a$  to 0.02%, (d) with cyclic loading,  $\epsilon_a$  to 0.02%.



**Fig.5** The stress-strain behavior of the specimens at optimum moisture content condition, (a) without cyclic loading, (b) with cyclic loading (c) without cyclic loading,  $\epsilon_a$  to 0.02%, (d) with cyclic loading,  $\epsilon_a$  to 0.02%.

the specimen is in a dense state, particles of different sizes fill each other dense, so that the particles squeezed tight, so in the shear increased the friction between the particles. And the particles in the shear band move or roll in the process of shear damage, then, stress-dilatancy is bound to occur. After the peak, because of the increase of stress-dilatancy behavior, the particles from the dense state gradually become loose state, the force on engagement between particle caused by stress-dilatancy behavior also gradually decreases until it disappears, so the phenomenon of stress reduction occurs.

**Fig.4 (a)** and **(b)** show the stress-strain behavior of the specimens under the dry condition, the deviator stresses were smaller in the specimen after cyclic loading than in those without cyclic loading, except at a confining pressure of 29.4 kPa.

In the dry condition, the confining pressure on 29.4 kPa indicates that after cyclic loading of the specimen, the particles are in closer contact, the compaction improves, and the strength increases. However, the case after cyclic loading decrease on the both confining pressures of 49.0 and 68.6 kPa. There are two possible reasons for this decrease in peak strength, i.e. change of packing state and reason of particle characteristics. The specimen without cyclic loading possesses a relatively loose packing state, which results in a larger strain hardening potential than the specimen with a dense packing state. In addition, since most of the particles are nearly spherical in shape. This would lead to a weaker interlocking and easier relative movement between soil particles, so the strength decreases<sup>24</sup>.

**Fig.5 (a)** and **(b)** show the stress-strain behavior of

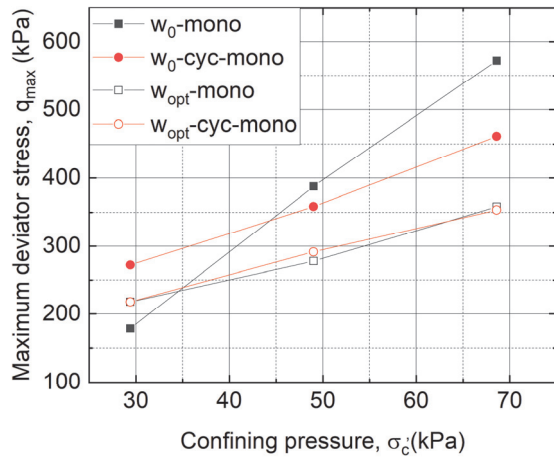
the specimens under the optimum moisture content condition, with or without cyclic loading, the deviator stress remains essentially unchanged. It was found that cyclic loading does not have a significant effect on the strength of the specimen in the optimum moisture content condition.

**Fig.4 (d)** shows that when the confining pressure is 49.0 and 68.6 kPa, the stress-strain curve after cyclic loading appears S-shaped before the deviator stress 60 kPa in the dry condition. It is shown in **Fig.5 (d)** that when the confining pressure is 29.4 and 49.0 kPa, the stress-strain curve after cyclic loading appears S-shaped before the deviator stress 60 kPa in the optimum moisture content condition; in general, the granular materials after cyclic loading and then monotonic triaxial compression test, the stress-strain curve appears S-shaped before the upper limit of stress amplitude of cyclic loading, the S-shape will appear on the stress-strain curve in the stress's range amplitude of the cyclic loading. This may be since the elastic deformation becomes better after cyclic loading<sup>25,26</sup>, it is easier to recover the original state when the test specimen is compressed by external force in the elastic deformation range.

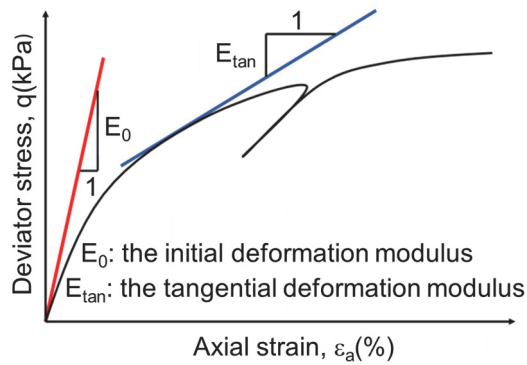
## (2) The maximum deviator stress, $q_{max}$

**Fig.6** shows the relationship between maximum deviator stress,  $q_{max}$  and confining pressure,  $\sigma'_c$ . The  $q_{max}$  increases with increasing  $\sigma'_c$  of independent of the pre-straining. The  $q_{max}$  after cyclic loading is essentially unchanged at the same confining pressure. According to the previous study<sup>26</sup>, the  $q_{max}$  of the common subbase course material is 225-300 kPa without cyclic loading under the optimum moisture

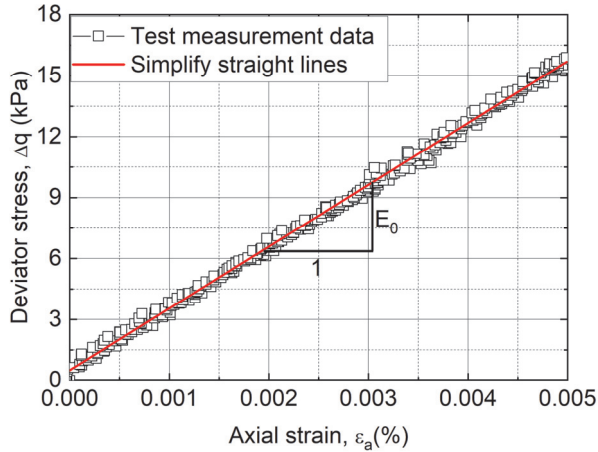




**Fig.6** The maximum deviator stress-confining pressure behavior of the specimens



**Fig.8** Definition of different deformation modulus

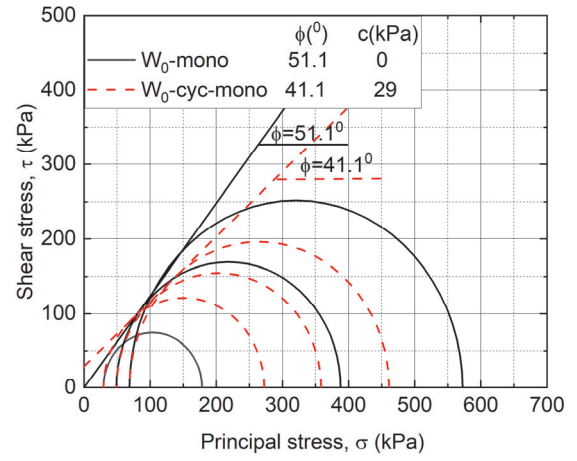


**Fig.9** Determination of the initial deformation modulus  $E_0$

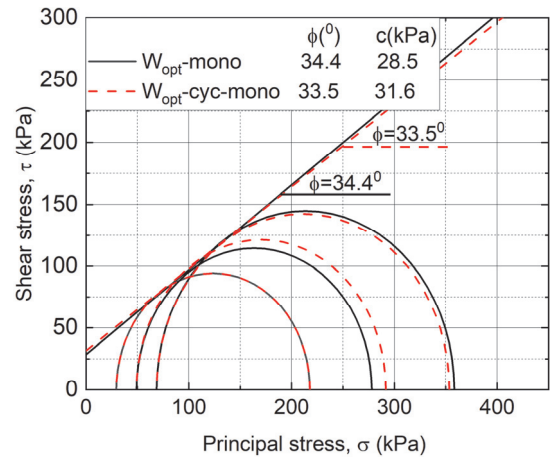
content at confining pressure of 29.4 kPa, and the case after cyclic loading is 150-275 kPa. The  $q_{max}$  of the material of this study is about 225 kPa under the same conditions, which is about 80 % of the common subbase course material.

**Fig.7 (a)** shows that the angle of shear resistance,  $\phi$  decreases after cyclic loading in the dry condition and the cohesion,  $c$  increases from 0 to 29 kPa after cyclic loading.

**Fig.7 (b)** shows that the  $\phi$  decreases and the  $c$  increase after cyclic loading in the optimum moisture



(a) Under the dry condition



(b) Under the optimum moisture content condition

**Fig.7** The Mohr's circles in peak stress state

content condition, but the increase and decrease is very small. It may be that after cyclic loading, the coarse particles underwent some sliding and were filled with fine material between them, which in turn reduced the occlusal force between the coarse particles, so the  $\phi$  decreased and the  $c$  is increased.

The shear strength characteristics of coarse aggregates can be described by the Mohr-Coulomb criterion<sup>(24),(28),(29)</sup>, while as a non-cohesive bulk material, there is no cohesion between particles, only frictional resistance, but many test results showed that if the linear strength criterion is used to represent the shear stress  $\tau$  of coarse aggregates, the linear intercept representing the  $c$  is not 0 kPa. Many scholars<sup>(30)-(32)</sup> believe that the  $c$  at this point is not explained by cohesion, but should be another manifestation of the occlusal force between coarse particles.

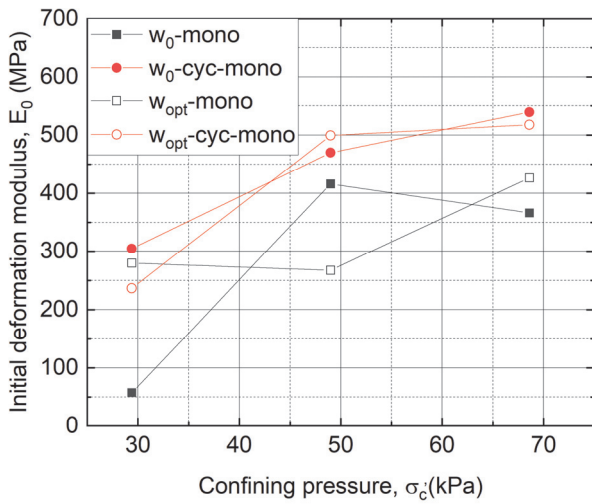
### (3) Initial deformation modulus and Tangent deformation modulus

In **Fig.8**, the definition of different deformation modulus is indicated.

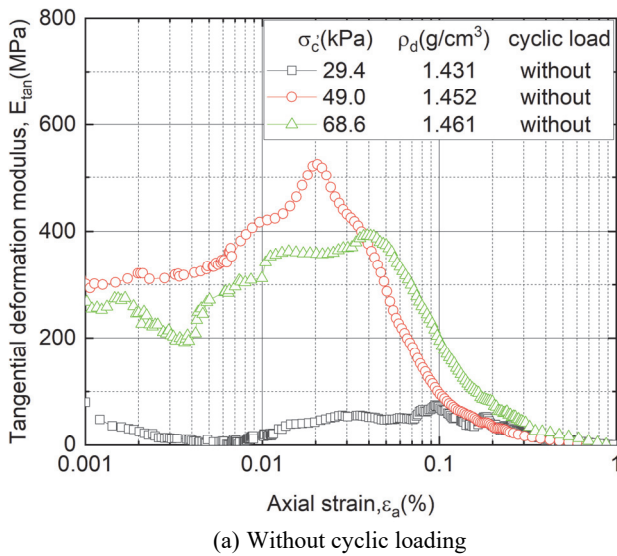
An example of determination is shown in **Fig.9**.

Coarse-grained soils exhibit linear elastic characteristics when the axial strain is less than  $10^{-5}$  under static or dynamic loading conditions according to the past research<sup>33</sup>). In this study, small unloading and re-loading is performed at the initial portion during monotonic loading. The initial deformation modulus  $E_0$  is defined as a slope of stress-strain relations at small strain level,  $\varepsilon_a=10^{-6}\sim 10^{-5}$ .

**Fig.10** shows the relationship between the confining pressure and the initial deformation modulus  $E_0$  increases with the increase of the confining pressure. This is because the confining pressure plays a certain lateral restraint effect, when the confining pressure is small, the resistance to particle movement is small, and the deformation resistance of specimen is weak. When the confining pressure is relatively large, the resistance to particle movement is large, and the deformation resistance of specimen is strong.



**Fig.10** The relationship between confining pressure and initial deformation modulus

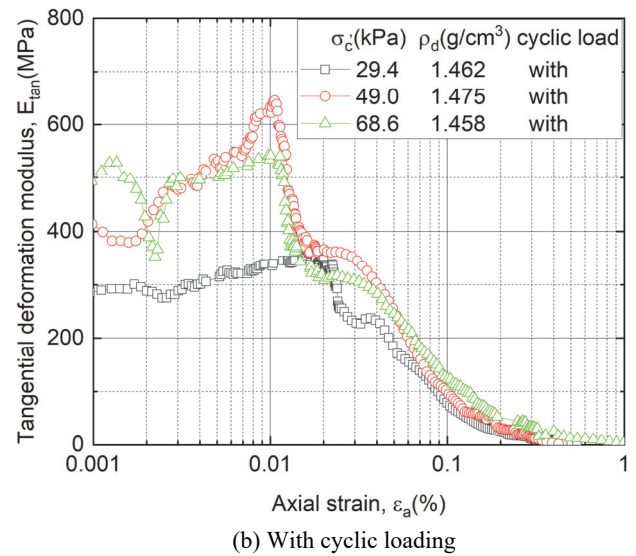


The initial modulus of the pre-straining compression curve is much higher than the case without cyclic loading. It is widely accepted that increase under stress level, a decrease in soil porosity or increase in the over-consolidation ratio would increase the stiffness of soils<sup>34)-36</sup>). In this study, the increase in the pre-straining elastic modulus is mainly because of the decrease in the void ratio of the specimen, which is induced by the densification effect of cyclic loading, and the increase in the over-consolidation ratio, which is resulted from the release of cyclic deviator stress. At the particle scale, after the soil specimen experiences large stress, the average distance between the centers of adjacent particles becomes smaller and the number of particle contacts per particle increases, so decreasing the average contact stress corresponding to a certain external load. Hence, the deformation in particle contacts decreases, and the stiffness of soil increases.

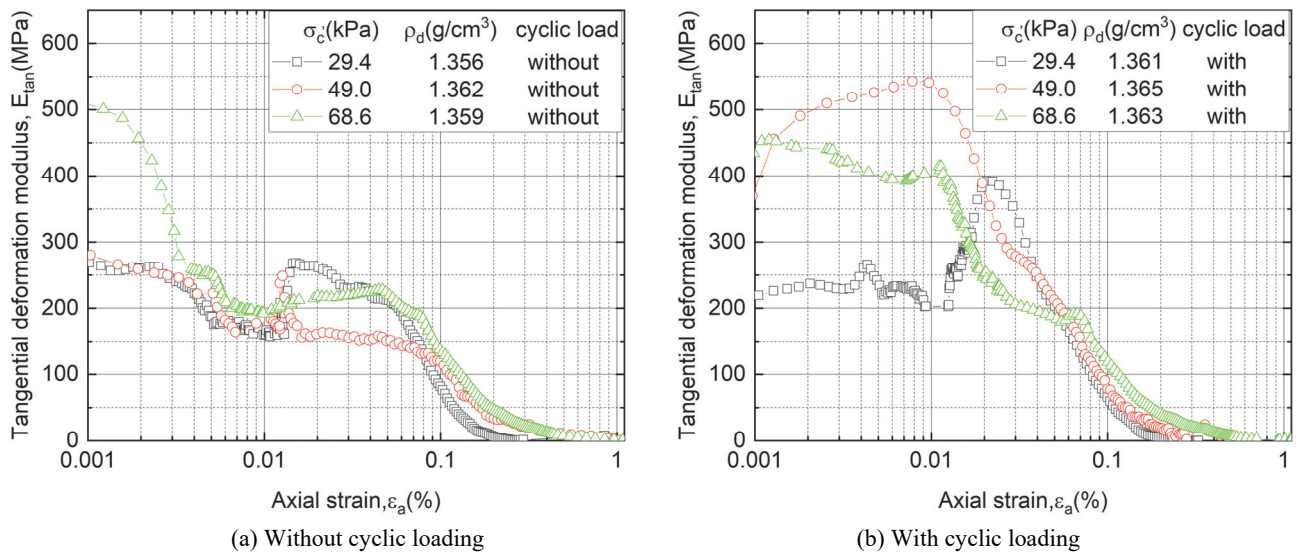
**Fig.11 (a) and (b)** show that the relationship between axial strain and tangential deformation modulus  $E_{tan}$  under the dry condition, the general trend of the  $E_{tan}$  with the increase in strain is a slow increase followed by a sharp decrease. However, it is found that when the confining pressure is 68.6 kPa, there is a sharp decrease followed by an increase in the initial strain at the beginning.

**Fig.12 (a) and (b)** show that the relationship between the axial strain and the  $E_{tan}$  under the optimum moisture content condition, the general trend of the  $E_{tan}$  with the increase of strain is that it first goes through slowing down, then increasing, and finally dropping sharply.

**Fig.11 and Fig.12** both show that the  $E_{tan}$  of specimens after cyclic loading were all larger than those



**Fig.11** The relationship between axial strain and tangential deformation modulus under the dry condition



**Fig.12** The relationship between axial strain and tangential deformation modulus under the optimum moisture condition

without cyclic loading. After cyclic loading, the stiffness of the lightweight subbase course material increases.

The cause of the out-of-trend data of the above is not test variability or test error because of 1 specimen in 1 test condition.

#### 4. CONCLUSIONS

It is the research purpose of this study that takes the development of a new subbase course lightweight materials for the pavement engineering field. Using this material instead of common materials, which can decrease the applied load on the soft road foundation. It is hoped that this material can reduce the residual settlement of road and bridge approach on the soft soil foundation. The triaxial test of this material is conducted under different conditions, and the following conclusions can be derived in this study.

- 1) The weight of the lightweight subbase course material is 85 % that of the common subbase course material, and the  $q_{max}$  is 80 % that of the common subbase material.
- 2) All specimens show an increase in  $q_{max}$  with increasing confining pressure and are characterized by strain softening.
- 3) The stress-strain curve after cyclic loading appears S-shaped before the deviator stress 60 kPa.
- 4) It was found that the  $q_{max}$  was greater in the specimen after cyclic loading than in those without cyclic loading in the dry condition, while cyclic loading does not have a significant effect on the  $q_{max}$  of the specimen in the optimum moisture content condition.
- 5) It can be seen that the angle of shear resistance

decreases after cyclic loading in the dry condition, and the cohesion increases from 0 to 29 kPa after cyclic loading, while the cohesion and the angle of shear resistance are stable in the optimum moisture content condition.

- 6) The angle of shear resistance of the lightweight subbase course material after cyclic loading is  $41.1^\circ$  and  $33.5^\circ$  under the dry condition and the optimum moisture content. It is considered that the requirement of the angle of shear resistance as road subbase course material is satisfied.
- 7) The initial deformation modulus  $E_0$  increases with the increase of confining pressure.
- 8) The initial stiffness of the pre-straining compression curve is much higher than that of the specimen compressed under the same pressure without cyclic loading.
- 9) The tangent deformation modulus  $E_{tan}$  after cyclic loading were all larger than those without cyclic loading.

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