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BEHAVIOR OF GRANULAR AND COMPRESSIBLE GEOMATERIAL UNDER CYCLIC LOADING

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ABSTRACT

Tire derived geomaterials (such as tire chips, tire shreds), the size of which range from 1 mm to 300 mm, are granular and compressible in nature. In actual geotechnical practice mostly large sized tire chips and/or tire shreds are used. However, in laboratory testing due to limitation of the size of the testing apparatus, researches on engineering properties are often limited to less than 2 mm particle size. The objective of this research was to confirm the effect of particle size on the compressibility and strength characteristics of such granular and compressible geomaterial, when used them in actual construction. To that end, a series of cyclic undrained triaxial tests and direct shear test were conducted on specimens of tire chips having different particle size (from small to large) using conventional as well as large scale testing apparatus. Cyclic triaxial test results show that as compared to the conventional geomaterials such as sand and clay, degradation of the equivalent shear modulus of tire chips is significantly less with increasing shear strain. Damping ratio also shows only a mild increase (less than 5%) with increasing shear strain as compared to the conventional geomaterials. From the static direct shear testing, it was found that the smaller the material grains are, the greater the shear strength. On the other hand, the greater the confining pressure, the smaller the difference in the maximum shear stress depending on the grain size. Grain size of the specimen seems to produce no marked difference in shear strength of tire chips in both the triaxial testing and the direct shear testing.

Keywords: compressibility, cyclic shear test, direct shear test, grain size, tire chips

INTRODUCTION

In recent years, granular and compressible geomaterials derived from scrap tires, have been gaining worldwide attention largely because of potential economic and environmental benefits. Advantages of using such materials in civil and geotechnical engineering practices are manifold. They are lightweight, have high vibration absorbing capacity, high elastic compressibility. Due to their granular nature they also have high hydraulic conductivity. In addition, they possess a very good thermal isolation potential. A novel application of granular and compressible tire chips can be found in Hazarika et al. (2008), who first coined the term *smart geomaterial* to describe such materials. Many works on material recycling of tire derived materials (tire chips and tire shreds) focusing on the materials properties and innovative applications are available (Edil & Bosscher, 1994; Hazarika, 2008; Hazarika & Yasuhara, 2007; Hazarika et al. 2010; Humphrey, 1998; Hyodo et al. 2007; Karmokar 2007; Karmokar et al. 2002; Kikuchi et al. 2005; Mitarai et al. 2006; Yasuhara, 2006; Yasuhara 2007: Yasuhara et al. 2006).

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Tire chips have dynamic characteristics that conventional materials do not possess, offering great possibilities for their use as geomaterials. However, sufficient data elucidating their material characteristics have not been collected to date. Tire chips is one of the tire derived geomaterials the size of which ranges from 1 mm to 30 mm. In actual geotechnical practice mostly large sized tire chips and/or tire shreds are used. However, in laboratory testing due to limitation of the size of the testing apparatus, researches on engineering properties are often limited to less than 2 mm particle size. Therefore, not many experimental data are available for tire chips having large grain size, which are often used in practice. The purpose of this research, therefore, was to test samples having larger grain size, which have been difficult to handle so far in laboratory because of the limitations of the testing apparatus. The data obtained from such tests are expected to serve as an invaluable reference for future design of structures wherein tire chips are used as geomaterials. To that end, a series of cyclic undrained triaxial tests and direct shear test were conducted on specimens of tire chips having different particle size (from small to large) using large-scale triaxial testing apparatus as well as large-scale direct shear testing apparatus, which was developed for this purpose.

DIRECT SHEAR TESTING APPARATUS

The newly developed large-scale shear testing apparatus is shown in Fig. 1. In addition to the conventional testing, it was designed for testing materials having larger grain size, which is difficult to perform using direct shear testing apparatus of conventional size. The shear box is divided into two parts: each 40 cm long, 20 cm wide and 15 cm deep. Furthermore, in this apparatus, it is possible to impart the dynamic loading in two directions (horizontal and vertical), and their simultaneous application can also be performed. Function generator can generate cyclic loading at a frequency ranging from 0.1 Hz to 0.5 Hz. The apparatus is designed to perform automatically using the touch type control panel shown in the figure. One salient advantage of this apparatus is that it can also be used as pull out testing apparatus of reinforced geomaterials.

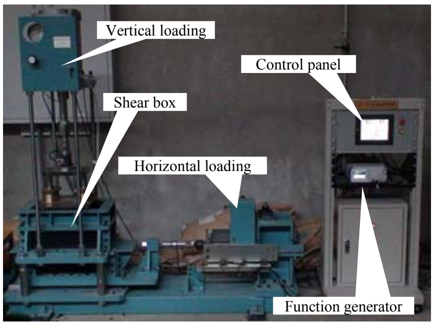


Figure 1. Large-scale direct shear and pull out testing apparatus

STATIC AND CYCLIC DIRECT SHEAR TEST

In this study, static direct shear test was performed first followed by repeated shear, targeted at tire chips of four different kinds and having different grain sizes. Tests were performed according to the procedure set forth in the manual for geotechnical testing (Japanese Geotechnical Society, 2003) for the conventional geologic materials.

Test materials

Tire chips used in the tests are shown in Figure 2. Four kinds of tire chips were used in the static shear test: (1) Sample No. 1: TC100H-a (20 mm), (2) Sample No. 2: TC300H (6.7 mm), (3) Sample No. 3: TC600H (3.3 mm), and (4) Sample No. 4: TC100H-b (26.5 mm). The numerical inside the brackets above indicate the maximum grain size D_{max} of the specimens. Figure 3 shows the particle-size distribution curve of the four specimens. Out of the four specimens mentioned above, two samples of larger size were used in the cyclic shear test: (1) Sample No. 1: TC100H-a and (4) Sample No. 2: TC100H-b.

（a） Sample No. 1 (TC 100H-a) **（b） Sample No. 2 (TC 300H)**

（c） Sample No. 3 (TC 600H) **（d） Sample No. 4 (TC 100H-b)**

Figure 2. Tire chips used in the testing

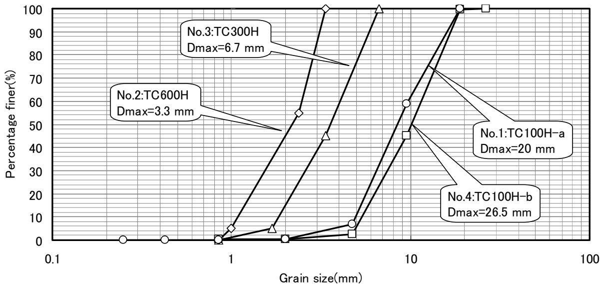


Figure 3. Particle-size distribution

Test method

Test specimens were produced using the materials shown in Fig. 2 under an air-dried state, and are prepared using the free falling technique. A constant mass of 18 kg was used for preparing the specimens in all the tests. Static shear tests were performed at three confining pressures of 100 kPa, 150 kPa, and 200 kPa. Before shearing the test specimens, they were compacted and consolidated for 10 min. Horizontal shearing is then applied at a speed of 0.25 mm/min until displacement reached 50 mm. Figure 4 presents the flow of the testing procedure. Recording of test results was started 1 min before the loading begins. After completion of the shearing, unloading was performed and recording was continued for another 30 min. For direct shear testing with repeated load, TC100H-a and TC100H-b were specifically selected, which have larger grain size among the materials used in the static direct shear test, and the shear strength due to repeated loading was evaluated. Direct shear tests with repeated load were performed at a confining pressure of 100 kPa. Before starting the shear, the specimen was compacted and then consolidated for 10 min. Horizontal shearing was performed thereafter at a speed of 1.00 mm/min until displacement reaches 30 mm in the compression and the tensile directions respectively. A total of 10 cycles of load was imparted to the specimens. Figure 5 shows the flow of the testing procedure. Table 1 summarizes the test conditions of the static shear testing and the shear testing with repeated load described above.

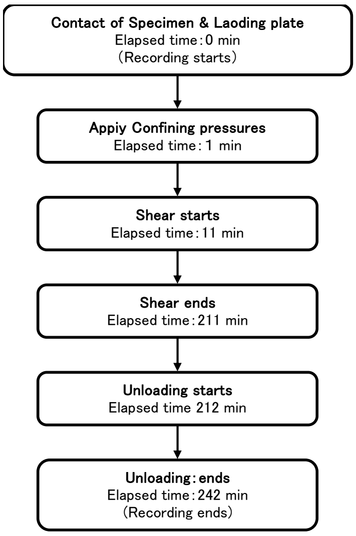


Figure 4. Flow of the static shear test

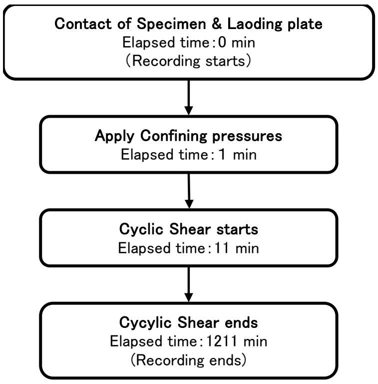


Figure 5. Flow of the repeated shear test

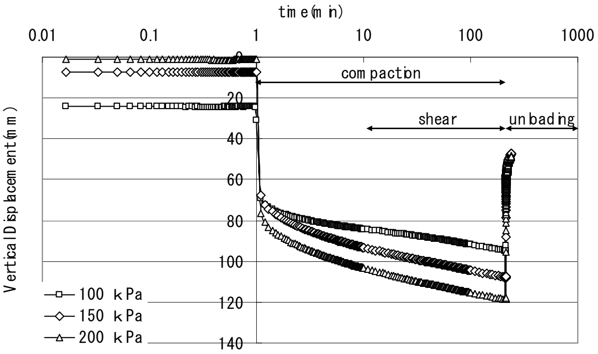
Table 1. Test conditions

Items	Static test	Cyclic test
Confining pressures (kPa)	100, 150, 200	100
Consolidation time (min)	10	10
Shearing speed (mm/min)	0.25	1.0
Maximum displacement (mm)	50	∓ 30

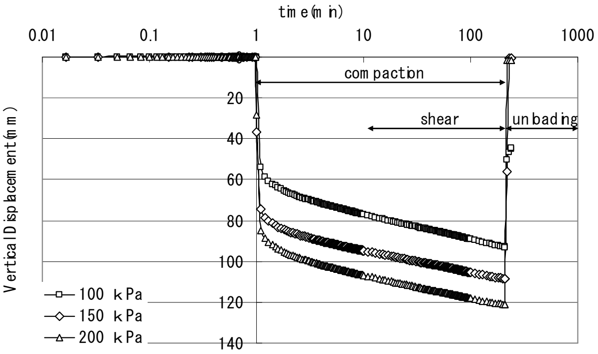
Test results and discussion

Compressive behavior under static loading

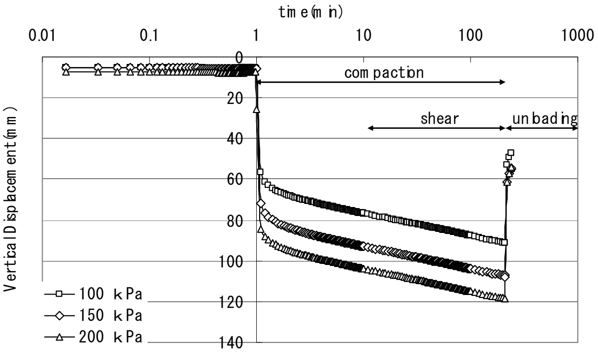
Figure 6 shows the relationship between the vertical displacement and time for each specimen (Specimen 1 ~4) in a semi logarithmic scale. The stages of deformations are marked into three distinct zones (consolidation, shear and unloading). In all the cases, vertical displacements show a constant decrease irrespective of the confining pressures. It is to be noted that the vertical displacements shown in these figures were measured at the upper portion of the shear box, and, therefore it is different from the displacement of the particle at the surface of the specimen.



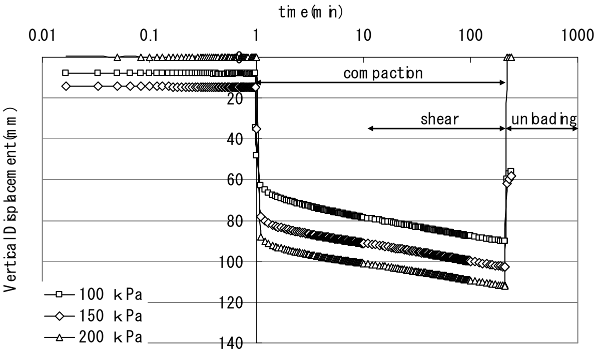
(a) Sample No. 1



(b) Sample No. 2

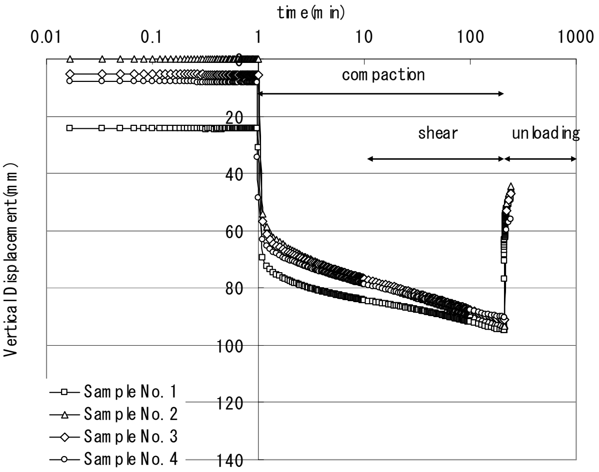


(c) Sample No. 3

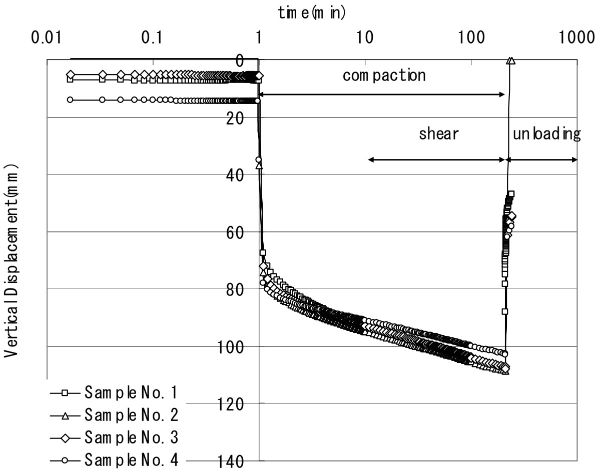


(d) Sample No. 4

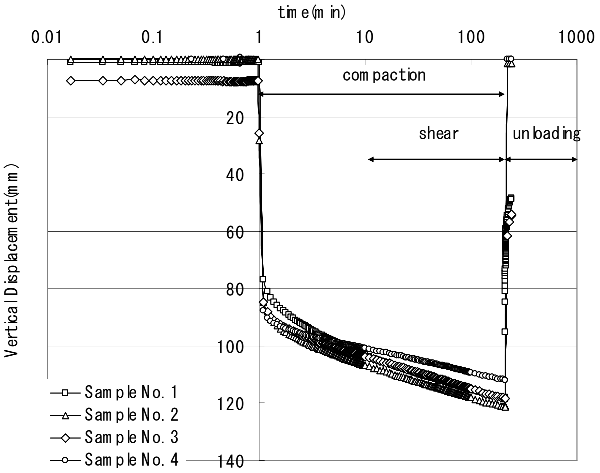
Figure 6. Vertical displacement vs. time



(a) At 100 kPa confining pressure



(b) At 150 kPa confining pressure



(c) At 200 kPa confining pressure

Figure 7. Vertical displacement under the same confining pressure

Figure 7 presents variations of the vertical displacement of each specimen when loading with the same confining pressure. It was observed that under confining pressure of 100 kPa, there is no significant difference of the final displacement in each specimen. However, as the confining pressure increases, the displacement becomes smaller in the TC100H-b specimen (specimen no. 4), which has larger grain size than others. Moreover, it is observed that materials with larger grain size show gentler slopes and the displacement converges at an early stage. Therefore, in actual practice, materials having larger grain size are considered advantageous from the viewpoint of the vertical displacement because the displacement due to loading is small and converges to the stable state quite early.

Table 2 shows the density at different stages of the shearing: at the start, at the end, and during unloading at different confining pressures. The larger the specimen's grain size, the higher the density of each specimen by free falling technique without any compaction. The density under compaction for any specimen converges to an almost equal value under loading with the same confining pressure. The density after unloading converges to approximately 0.70 g/cm^3 for all the cases, which is greater than the maximum density 0.55 g/cm^3 of tire chips (2 mm average grain size) that is reported in the relevant literature (e.g. Kobayashi & Yajima, 2007). A compacted specimen has a high density that cannot be achieved using conventional tamping method even after unloading.

Table 2. Density at different confining pressures

Specimen	Confining pressures (kPa)	Density(g/cm^3) start of shear	end of shear	30 min. after unloading
No.1:TC100H-a	100	0.77	0.80	0.69
	150	0.80	0.84	0.69
	200	0.83	0.88	0.69
No.2:TC300H	100	0.76	0.79	0.69
	150	0.80	0.84	0.70
	200	0.83	0.88	0.70
No.3:TC600	100	0.76	0.80	0.68
	150	0.80	0.84	0.69
	200	0.84	0.89	0.68
No.4:TC100H-b	100	0.76	0.79	0.71
	150	0.79	0.83	0.71
	200	0.83	0.86	0.71

Figure 8 shows the change of vertical displacement with time for the specimen no. 4 (TC100H-b). Vertical displacement about 20 hr after loading is found to be approximately 110 mm. This implies a compression of about 20 mm after 200 min of compression. Therefore, it can be conferred at this stage that no substantial compression of the materials is expected to occur even after loading for a long period of time. However, it is necessary to obtain test results over a longer compression period to arrive at a definite conclusion.

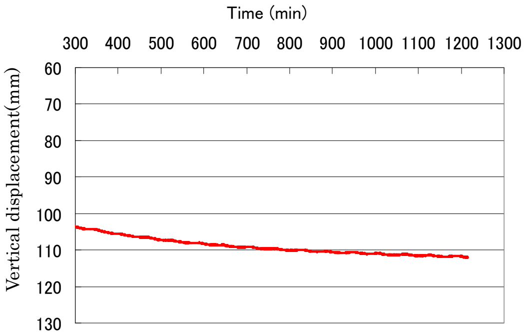
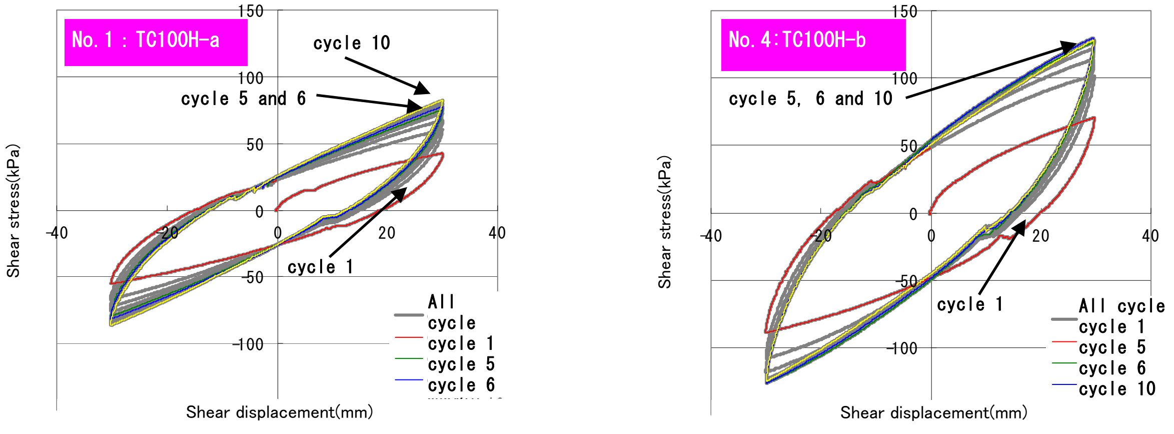


Figure 8. Vertical displacement during static shear test (Sample 4: TC100H-b)

Direct shearing under repeated loading

Figure 9 shows the stress displacement relationship of the large size specimens (Sample 1 & Sample 4) under repeated loading. In both the specimens, the shear force becomes large as the number of cycle increases. As the confining pressure increases, the larger the specimen's grain size, the smaller the displacement caused by the loading. Observations indicate that the larger the grain size a material has, the gentler the curve and the earlier the convergence of displacement. The shear force at the end of 10th cycle is approximately one and half times that of at the end of 1st cycle. The increase in the shear force tends to converge as the number of cycle increases. No significant increase in shear force is observed beyond 6th or 7th cycles. It can be presumed that the gaps caused by the repetitive shear in the same face of the tire chips particles, cause a marked increase in density, which cannot be achieved under usual compaction. Therefore, it can be said that the repetitive loading rather aids in developing good densification of tire chips.



(a) **Sample No. 1**　　(b) **Sample No. 4**

Figure 9. Stress-displacement relationship for each specimen

UNDRAINED CYCLIC TRIAXIAL TEST

A series of undrained cyclic triaxial tests was conducted on large size specimen to understand the shear behavior and strength characteristics of tire chips. Such behavior was studied in detail by Hyodo et al (2007) and Kawata et al. (2007). However those studies were limited to conventional triaxial testing apparatus, in which large size tire chips could not be used due to the problems of membrane penetration. In this study, the large scale cyclic triaxial testing apparatus belonging to Obayashi Corporation, Tokyo, Japan was used (Fig. 10). The triaxial cell is 30 cm in diameter and 60 cm in height and can test materials up to a maximum grain size of 53 mm. Two large size specimens (Sample no. 1 and Sample no. 4) used in the direct shear tests described above was selected as the target of this study.

Specimen preparation and test method

At first, tire chips were washed with detergent to remove the impurities that adhered to their surfaces, and then were exposed to warm air to make them dry. The test specimen was prepared by placing tire chips inside the mold in six layers, with each layer compacted at a prescribed number of times by dropping a rammer from a prescribed height to control the compaction energy, which is given by the following expression.

$$E_c = \frac{W_R \bullet H \bullet N_L \bullet N_B}{V} \tag{1}$$

In which, W_R is the rammer weight (0.098N), H is the drop height, N_L is the number of layers (= 6), N_L is the number of drops per layer (= 88) and V is the volume of the mold. Compaction was thus performed at controlled compaction energy of 550 kJ/m^3. The densities of the specimens thus obtained were 0.71 g/cm^3 and 0.68 g/cm^3 for the Sample No. 1 and Sample No. 4 respectively.

(a) Overview of the testing machine **(b) View of the prepared test sample**

Figure 10. Large scale cyclic triaxial testing apparatus (Courtesy: Obayashi Corporation, Tokyo, Japan)

After transferring the specimens to the triaxial cell, they were isotropically consolidated at confining pressure of 100 kPa and undrained cyclic tests were conducted at loading frequency of 0.1 Hz for 20 cycles. Consolidation curves of each specimen are shown in Fig. 11. Table 3 presents the densities of the specimens at different stages (sample preparation, before consolidation and after consolidation). For small size particles the densities were comparably small as reported by Kobayashi and Yajima (2007). Fig. 12 presents the densities of the specimens during the sample preparation, before consolidation and after consolidation. From this figure it can be observed that with increasing confining pressure, the densities of the specimens decrease. Also, the grain size is not seen to influence significantly such tendency. From Table 3, if we observe the compressive behavior during consolidation, we can see that the height of the specimen decreased by about 4.5 ~ 4.8 cm due to consolidation, which amount to a strain of 7.5~7.9%. On the other hand, if we consider the volume, as compared to the initial state, about 20% volume compression took place. As a result, the densities after consolidation were 0.875 g/cm^3 and 0.850 g/cm^3 for the Sample No. 1 and Sample No. 4 respectively.

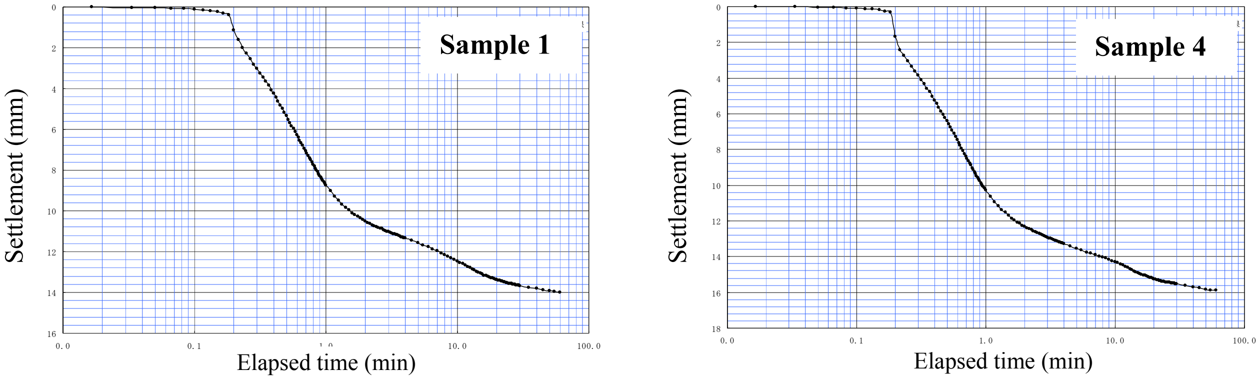


Figure 11. Settlement curve during consolidation

Table 3. Densities at various stages

Items		Sample 1	Sample 4
During sample preparation	Height (cm)	60.3	60.3
	Diameter (cm)	29.98	29.98
	Volume (cm^3)	42576.2	42576.2
	Density(g/ cm^3)	0.688	0.679
Before consolidation	Height (cm)	56.91	57.32
	Volume (cm^3)	36893.3	37107.3
	Density(g/ cm^3)	0.795	0.779
After consolidation	Height (cm)	55.51 (Axial strain 7.9 %)	55.73 (Axial strain 7.6 %)
	Volume (cm^3)	33483.3 (Volumetric strain 21.3 %)	34017.3 (Volumetric strain 20.1 %)
	Density(g/ cm^3)	0.875	0.85

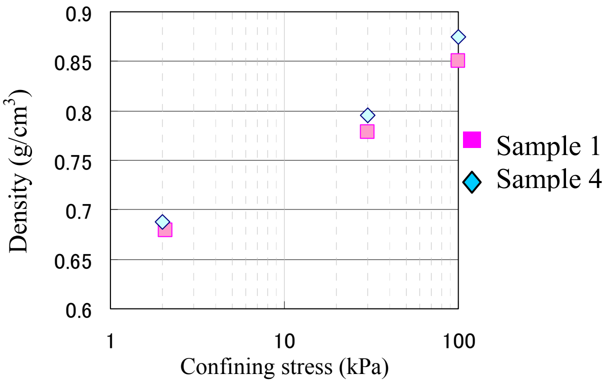


Figure 12 Relationship between the specimen density and the confining pressure

Cyclic shear properties

Typical stress-strain curves obtained from cyclic triaxial tests are shown in Fig. 13. Both the specimens show linear elastic behaviour even at large axial strain. Also, there is no dramatic increase of the strain amplitudes, even with the increase of the number of cycles. Fig. 14 shows the relationship between the equivalent Young modulus (E_{eq}) and single amplitude strain (ε_a) obtained from the test results for the two specimens. In the same figures the thick lines represent the relationship given by the Hardin-Drnevich Model (1972). The equivalent Young modulus values given by Hardin-Drnevich Model is found to be almost same for the two specimens, implying that the grain size of tire chips do not influence these values. Also, the equivalent elastic modulus decreases with increasing strain and the hysteretic damping ratio increases with increasing strain amplitude. This implies that the cyclic shear strength of tire chips are strain dependent.

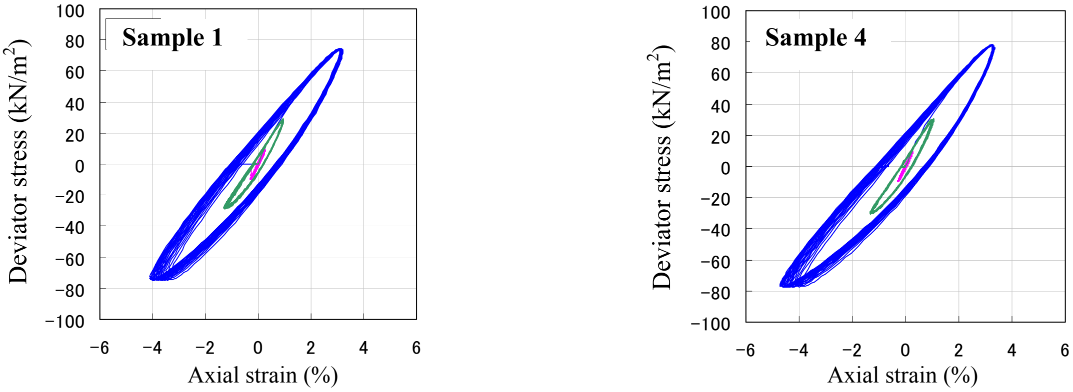


Figure 13 Cyclic stress-strain relationship

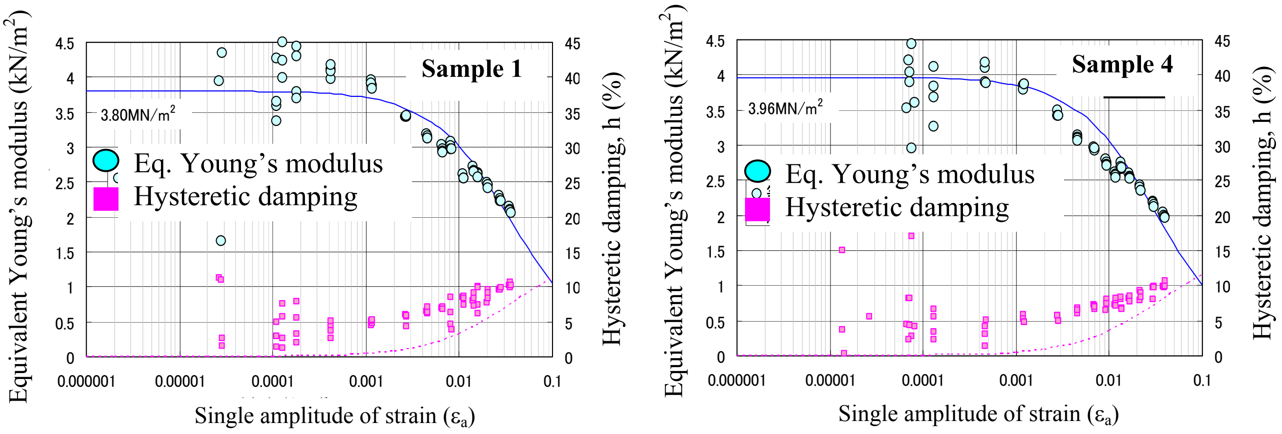


Figure 14 Relationship between equivalent Young's modulus and strain amplitude

Fig. 15 shows the relationship between the normalized shear modulus (G_{eq}/G_{eq0}) and shear strain (γ) for the Sample 4. Fig. 16 shows the relationship between the damping ratio and shear strain for the same specimen. In the same figures, the relevant data for sandy soils given by Ishihara (1976) were also plotted. From these figures, it can be seen that the G-γ curve lies well above the sandy soils. Also, the shear strain at which the shear modulus starts depleting is rather high. In the case of the damping ratio, the h-γ curve lies well below those of the sandy soils. In this case too, the shear strain at which the damping ratio starts to increase is rather high. Therefore, it can be inferred that even though tire chips posses strain dependent characteristics, as compared to other granular geomaterials the characteristics is not dominant.

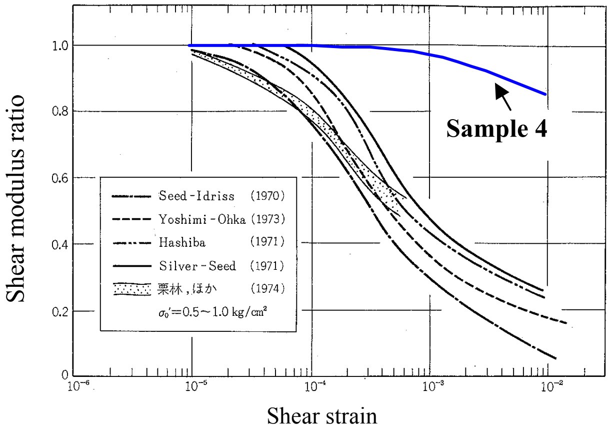


Figure 15 Strain dependency of shear modulus (*After* Ishihara, 1976)

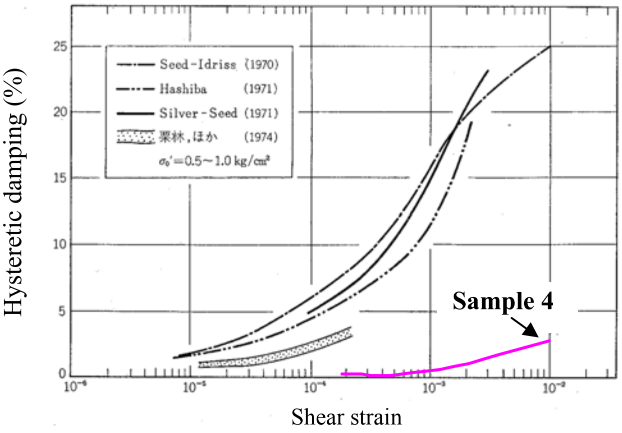


Figure 16 Strain dependency of hysteretic damping (*After* Ishihara, 1976)

CONCLUDING REMARKS

In this study, the influence of grain size on the material strength and deformation characteristics of granular and compressible materials such as tire chips were evaluated through the static and repetitive direct shear testing as well as the cyclic triaxial testing. From the static direct shear testing, it was found that the stress–displacement relation during shearing is highly ductile and exhibits strain hardening. The greater the confining pressure, the higher the development of maximum shear stress. On the other hand, the greater the confining pressures the smaller the difference in the maximum shear strength among the specimens. Grain sizes of the specimens produce no marked difference in shear strength of tire chips. Observations also indicate that the larger the grain size a material has, the gentler the stress-strain curve under repeated loading *and the earlier the convergence of displacement.*

Cyclic triaxial test results reveal that the cyclic strength of tire chips is strain-dependent. As compared to the conventional geomaterials such as sand and clay, degradation of the equivalent shear modulus of tire chips is significantly less with increasing shear strain. Damping ratio also shows only a mild increase (less than 5%) with increasing shear strain as compared to the conventional geomaterials. The effect of grain size on the material strength, however, was not clearly observed. Though not significant, density was found to be affected by the grain size.

Materials having larger grain size are considered advantageous from the viewpoint of the vertical displacement because the displacement due to loading is small and converges to the stable state quite early. Therefore, for practical use tire derived recycled materials having larger grain sizes are more advantageous.

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