Compression and shear behavior of tire chips and prevention effect of liquefaction

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ABSTRACT

In order to investigate the fundamental properties of pure tire chips and their mixture with sand, a series of monotonic shear and cyclic triaxial tests was performed. From the results of the monotonic drained shear tests on pure tire chips, linear development of axial and volumetric strains were observed during loading up to 20% axial strain in both types of tire chips. It was further observed that the volumetric strain induced by shear loading recovered to zero during unloading. It is considered that the volumetric strain induced by shear was not dilatancy by rearrangement of particles but due to the stretching of tire chips. In the monotonic undrained shear tests using the mixed sand and tire chips, the mixtures show completely different behavior to pure sand, this due to the particles of the tire chips being smaller than that of the sand. The matrix of the material was governed by tire chips when the tire chip fraction was greater than 0.3. From the results of the undrained cyclic triaxial tests of pure tire chips, there was hardly any development of pore water pressure, resulting in non-liquefaction.

Keywords: Tire chips, Volume change, Liquefaction

1 INTRODUCTION

When the Great East Japan Earthquake occurred in 2011, many structures suffered damage due to liquefaction. Tire chips, which are from shredded waste tires, are going to be used for improvement of foundation soil by isolating seismic wave propagation and mitigating liquefaction. Over one billion waste tires are produced yearly around the world, with this number ever increasing, and therefore the reuse of tire chips as a geotechnical material is being considered in order to reduce waste. Some research on the shear behavior of tire chips has already been conducted (Yajima, J. et al. (2009), Kikuchi, Y. et al. (2008), Kawata, S. et al. (2007)), although the mechanical properties are not yet fully understood. Mitigation of the liquefaction of sand by using a mixture of tire chips and soil has also been investigated (Hazarika, H. et al. (2007), Hyodo, M. et al. (2007), Kaneko, T. et al. (2010)). In this study, two kinds of tire chips with different diameters were investigated to understand the shear behavior of pure tire chips. Furthermore, the shear behavior of sand and tire chip mixtures was also investigated using triaxial testing equipment under CU conditions. From the results, the dilatancy behavior and mechanism of pore water pressure generation of the tire chips could be observed. In addition, the development of excess pore water pressure during undrained cyclic triaxial testing was investigated and compared with the monotonic shear results.

2 SAMPLE AND EXPERIMENT PROCEDURE

2.1 Testing Material

In this study, two types of tire chips from waste tires of large trucks, with the maximum diameters of 0.5mm (Fig.1a) and 2mm (Fig.1b), were used. The two types are termed tc for the 0.5mm chips and TC for the 2mm chips. The reason for using these two types of tire chips is that 2mm is larger than the largest diameter of the sand used in the mixtures, whilst 0.5mm is smaller than the smallest diameter.

![Fig. 1. tire chips](http://doi.org/10.3208/jgssp.JPN-141)

The particle density of the pure tire chips and sand-tire chip mixtures are shown in Table 1, along with the maximum and minimum void ratios. In the table, the ratio of sand to tire chips in the mixture is shown. The value between 0-1 represents the percentage of tire chips by volume between 0%-100%. In Fig. 1, the grain size distribution curves for tc and...
Table 1. Physical properties of samples

<table>
<thead>
<tr>
<th>Tire chips fraction</th>
<th>$e_{\text{min}}$</th>
<th>$e_{\text{max}}$</th>
<th>$\rho_s$ (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tc:0</td>
<td>1.02</td>
<td>1.33</td>
<td>2.64</td>
</tr>
<tr>
<td>tc:0.3</td>
<td>1.33</td>
<td>1.51</td>
<td>2.21</td>
</tr>
<tr>
<td>tc:0.5</td>
<td>1.51</td>
<td>1.89</td>
<td>1.91</td>
</tr>
<tr>
<td>tc:0.7</td>
<td>1.89</td>
<td>2.69</td>
<td>1.18</td>
</tr>
<tr>
<td>tc:1.0</td>
<td>2.69</td>
<td>0.68</td>
<td>2.64</td>
</tr>
<tr>
<td>TC:0.7</td>
<td>1.02</td>
<td>1.21</td>
<td>1.15</td>
</tr>
<tr>
<td>TC:0.5</td>
<td>1.21</td>
<td>1.28</td>
<td>1.60</td>
</tr>
<tr>
<td>TC:0.3</td>
<td>1.28</td>
<td>1.07</td>
<td>1.60</td>
</tr>
<tr>
<td>TC:1.0</td>
<td>1.07</td>
<td>1.59</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Fig. 2. Grain size distribution curves of samples

2.2 Specimen Preparation and Test Procedure

A series of monotonic triaxial tests with confining pressures of 50kPa, 100kPa and 200kPa under CU and CD conditions were performed. The size of the triaxial specimen was 5cm in diameter and 10cm in height and was prepared using tamping, divided into 13 layers. The target initial void ratio was between 0.65 to 0.70 for TC and between 0.76 to 0.88 for tc. However, as the material is very light and fine, it was difficult to prepare the specimen to the given relative density, and so trial and error was used in order to prepare the sample to the required relative density. For the tire chip and sand mixtures, samples were prepared using a compaction energy of 408kJ/m$^3$ to give dense samples. In order to have a water saturated specimen, CO$_2$ gas was injected and de-aired water was circulated through the specimen before 200kPa of back pressure was applied to ensure a B-value of over 0.95. After preparing a saturated sample, consolidation was performed under a given confining stress and shear tests were carried out to apply an axial load at 0.1mm/min axial strain speed. During loading tests, the test was performed up to 20% of axial strain and unloading tests were then performed back to an axial strain of 0%.

3 MONOTONIC SHEAR LOADING AND UNLOADING TEST

3.1 Monotonic Shear Test with Pure Tire Chips

The relationship between deviator stress, volumetric strain and axial strain for shear loading and unloading tests are presented in Fig. 3a and 3b for tc and TC, under confining stresses of 50kPa, 100kPa and 200kPa. The solid lines represent shear loading and the dashed lines represent unloading. In comparison of the results of tc and TC, TC displays a slightly higher strength. This is because the initial void ratio of TC was smaller than that of tc, and so the specimen was denser. The shape of the stress and strain curve shows an upwards bending trend due to increase of mean principal stress under constant lateral stress test conditions. During unloading, a hysteresis curve was drawn and some residual plastic strain was induced at $q=0$. In the relation between volumetric strain and axial strain, the loading results are again drawn as a full line whilst the unloading stage is represented by a broken line. The induced volumetric strain under shear increased linearly, and during unloading the volumetric strain decreased linearly along the same path as during loading. A small magnitude of residual volumetric strain due to unloading appeared in tc although not for TC. In these results, almost all volumetric strain due to shear loading did not develop because of dilatancy caused by rearrangement of particles, but instead as a result of elastic deformation of each particle during loading.

Fig. 3. Monotonic shear tests (Drained Condition)

Deviator stress-axial strain relation

Fig. 4 shows deviator stress and axial strain relationships for tc and TC under undrained monotonic shear loading/unloading tests at various confining stresses. The solid lines represent the shear loading stage and the dashed lines represent unloading. The stress and strain relationship curve shows linear behavior but gives a downwards bending curve. This is due to the development of pore water pressure. The hysteresis curve during unloading appeared similar to drained tests.

Fig. 4. Monotonic shear tests (Undrained Condition)

Deviator stress-axial strain relation
In Fig. 5, the effective stress paths of shear loading tests and unloading tests are presented. It is shown that the development of induced pore water pressure for tc is larger than that of TC. Also, it can be observed in the unloading test results that residual pore water pressure remains at q=0 for tc, although with TC there is almost no residual pore water pressure visible. From these results, it can be seen that induced pore water pressure due to negative dilatancy did not develop in TC, whereas a small amount of residual pore water pressure appeared in tc due to dilatancy. These results corresponded to the volumetric strain behavior for drained test results.

3.2 Monotonic Drained and Undrained Shear Tests for Sand-Tire Chips Mixture

Specimens were prepared with varying proportions by volume of tire chips tf=0, 0.3, 0.5, 0.7 and 1.0. Specimens were prepared using a tamping method with constant tamping energy. A series of monotonic triaxial tests were performed with a confining stress of 100kPa under CU and CD conditions. The relationship between deviator stress, volumetric strain and axial strain for sand-tire chip mixtures with various fractions of tire chips for tc and TC are shown in Fig. 6. A drastic decrease in strength appeared when the tire chip fraction was over 0.5, especially for the small particle mixture tc. The volumetric strain for pure sand shows dilative behavior whereas tire chips show contractive behavior. When the tire chips fraction was 0.3, the mixture displays similar behavior to pure sand, whereas for mixtures with a tire chips fraction of more than 0.5, the behavior displays a contractive manner in the same way as pure tire chips.

In Fig. 7, the deviator stress and axial strain for undrained test results are presented for tc and TC. When the tire chips fraction is more than 0.3, a drastic decrease of strength occurs in both materials.

Deviator stress for the mixtures are plotted against mean normal effective stress for tc in Fig. 8a and TC in Fig. 8b. In Fig. 8a, the mixture of the tire chips shows completely different behavior to pure sand; this due to the particles of the tire chips being smaller than that of the sand. The matrix of the material was governed by tire chips when the tire chip fraction was greater than 0.3. On the other hand, in the case of TC, when the tire chip fraction was 0.3, some part of sand aggregation was left so that the behavior was similar to that of sand. Further, when the tire chip fraction was more than 0.5, the whole matrix was governed by the tire chips.

4 UNDRAINED CYCLIC TRIAXIAL TESTS

A series of undrained cyclic triaxial tests were performed on tire chips and sand mixtures with varying tire chips fractions of 0, 0.3, 0.5, 0.7 and 1.0. In Fig. 9, the effective stress paths for each tire chips fraction are presented for both tc and TC. The development of pore water pressure decreased with increasing tire chip fraction in these figures. In the case of a tire chip fraction of 0 and 0.3, the material shows almost liquefaction at the final stage of the cyclic loading, whereas in mixtures with tire chip fractions of more than 0.5, no liquefaction occurred. The increment of axial strain at each cycle was plotted against number of cycles for the small and large tire chips mixtures with various tire chips fractions. In both figures, a large
increment of axial strain appeared at the beginning of cycling for pure tire chips and $t_f=1.0$ due to tire chips having low stiffness.

![Graphs showing deviator stress vs. mean normal effective stress for different tire chip fractions.](image)

3) From the undrained cyclic triaxial tests, in the case of a tire chip fraction of 0 and 0.3, the material shows almost liquefaction at the final stage of the cyclic loading, whereas in mixtures with tire chip fractions of more than 0.5, no liquefaction occurred.

**REFERENCES**


**5 CONCLUSIONS**

In this study, two kinds of tire chips with different diameters were investigated to understand the shear behavior of pure tire chips. The following were the main findings obtained from these tests.

1) From the results of monotonic shear tests for pure tire chips, the deviator stress of both tc and TC showed linear behavior with increasing axial strain. During unloading, a hysteresis curve was drawn and some residual plastic strain was induced.

2) In sand-tire chip mixtures, for both drained and undrained tests, the mixture of the tire chips shows completely different behavior to pure sand, this due to the particles of the tire chips being smaller than that of the sand. The matrix of the material was governed by tire chips when the tire chip fraction was greater than 0.3. On the other hand, in the case of TC, when the tire chip fraction was 0.3, some part of sand aggregation was left so that the behavior was similar to that of sand. Further, when the tire chip fraction was more than 0.5, the whole matrix was governed by the tire chips.