Large-Scale Shear Testing of Tire Derived Aggregates (TDA)

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ABSTRACT: This paper reports a large-scale direct shear testing of tire derived aggregates (TDA) of large sizes (25 to 75 mm). TDA are pieces of processed and shredded waste tires that can be used as lightweight and quick fills for embankments, subgrades, and retaining wall backfills. A large-scale direct shear apparatus was built to obtain the shear strength of the large-sized material. The shear box dimensions were 78 cm wide, 80 cm long, and 122 cm tall. The lower shear box was driven by a hydraulic piston while the upper shear box remained stationary. The horizontal shear forces, shear displacements, and vertical forces were recorded by an automatic data acquisition system. Four normal loads were applied on the TDA to simulate overburden pressures of 24, 48, 96, and 144 kPa (or 500, 1000, 2000, and 3000 lb/ft²). Duplicate tests were performed to verify the repeatability. Under each normal stress, the shear stress vs. deformation curve was plotted, and the maximum shear stress was obtained. Mohr-Coulomb failure criterion was developed and the cohesion and friction angle were obtained.

INTRODUCTION

The US Federal Highway Administration (FHWA 1997) estimated that approximately 280 million tires are discarded each year by American motorists, 40% of which are disposed in landfills, stockpiles, or illegal dumps. In California, for example, approximately 44.8 million reusable and waste tires are generated annually with a little fewer than 250,000 waste tires remaining in stockpiles throughout California (CalRecycle 2010). These stockpiles pose a potential threat to the public health, safety, and environment. Tire shreds, also known as tire derived aggregates (TDA), are pieces of processed and shredded waste tires that have a “basic geometrical shape and range between 50 mm (2 inch) and 305 mm (12 inch) in size and are intended for use in civil engineering applications” (ASTM D6270-08). Some
of the applications include lightweight and quick fills for embankments, subgrades, and retaining wall backfills. TDA are typically compacted using rollers/compactors. TDA are lightweight, their typical density in field applications is from 560 to 1040 kg/m³ (or 35 to 65 lb/ft³). Therefore, they exert less overburden pressures on weak and collapsible soils than conventional backfills. TDA have low earth pressure, good thermal insulation, and good drainage. Moreover, TDA do not need moistening for compaction and are a free-draining material; therefore, they can be used as a quick fill even in wet weather conditions.

There are two types of TDA that are commonly categorized in the practice: Type A with a maximum size of 75 mm (3 inch) and Type B with a maximum size of 305 mm (12 inch). TDA of different sizes have been widely studied as alternative backfills for the past twenty years; and vast literature references are available (e.g., Humphrey and Manion 1992; Humphrey 1998; Bosscher et al. 1992; Tweedie et al. 1998; Strenk et al. 2007; Tandon et al. 2007). These studies expanded the knowledge on the mechanical characteristics and in-situ performance of embankments and retaining walls using tire shreds or chips. In a recent study, Pando and Garcia (2011) summarized the shear strengths of the tire crumbs (2 to 13 mm or 0.08 to 0.5 inch) under various confining pressures obtained by previous researchers. Moreover, they reported the ranges of effective cohesion (0-14 kPa) and effective friction angle (14.9-9.2 deg) of crumbs of maximum size of 4.5 mm when the material was subjected to confining pressures ranging from 25 to 100 kPa at 20% strain. Mixture of shredded tires and sand is another backfill alternative and its static responses (stress, deformation, strength) have also been investigated (e.g., Foose et al. 1996; Bosscher et al. 1997; Lee et al. 1999; Wartman et al. 2007).

Large-scale direct shear tests were also conducted on TDA and TDA-sand mixtures (Humphrey et al. 1993; Foose et al. 1996; Bernal et al. 1997). In these studies, the dimensions of the shear boxes were up to 30 cm by 30 cm by 30 cm; and the maximum shear displacement was 9.0 cm. These studies provided comparable shear resistances of TDA of large sizes. Meanwhile, Bernal et al. (1997) noted that the rubber-sand and tire shreds specimens did not develop well-defined peak shear within the allowable shear displacement of 6 cm in their study. And boundary effects of the shear devices could be more pronounced with large-sized TDA such as 75 mm in length. A larger shear device with larger displacement may provide an improved knowledge of the shear resistance developments of TDA of large sizes (25 to 75 mm) under wide range of vertical overburden stresses. Therefore, the objective of this research is to obtain the shear resistances of large-sized TDA using a large-scale shear testing device. The shear device can accommodate specimens that are 79 cm wide, 80 cm long, and 122 cm tall; the maximum horizontal shear displacement is 18 cm, and the vertical pressure can be up to 144 kPa.

MATERIALS AND METHODOLOGY

Materials
The TDA were provided by the California Department of Resources Recycling and Recovery (CalRecycle). They were produced using tire shredders and have metal wires extruding from pieces. Figure 1 shows a photo of the TDA. The size range is 5 to 100 mm; Figure 2 shows the size distribution. The TDA were clean and there were no oil or chemical residues on the material. Sand was also tested as a control material. The sand used in this research was a uniform clean sand, with fine content of 0%, \( d_{10} = 0.25 \text{ mm} \), \( d_{30} = 0.45 \text{ mm} \), and \( d_{60} = 0.80 \text{ mm} \). In the practice, TDA are characterized using size distributions. The commonly used tire shredders typically produce TDA with similar shape and aspect ratio. Therefore, the effect of various shapes and aspect ratios of TDA on the shear resistance was not studied. In this research, only the shear resistance of TDA was investigated; the shear resistance of TDA in contact with other materials (such as soil, concrete, geosynthetics) and the shear resistance of TDA and sand mixtures were not investigated.

**FIG 1.** Photo of TDA

**FIG 2.** Size distribution of TDA

### Experimental Setup and Instrumentation

The large-scale direct shear test equipment is shown in Figure 3. The shear box was comprised of two half-boxes. The dimensions of each box were 79 cm wide, 80 cm long, and 61 cm tall. The upper box was bolted on the frame of a compression rig and was stationary. The lower box had guide rails on its bottom; it was driven by a horizontal hydraulic piston and can slide smoothly in the horizontal direction. Each box was constructed using strong structural steel frame to withstand large vertical and horizontal loads. The walls of the shear box were made of 2.54 cm (1.0 inch) plywood to ensure no flexing of the sidewalls. Smooth plastic sheets were lined on the inside of the four walls of the shear boxes to reduce vertical friction, so that the entire normal force can be applied to the materials in the box. The vertical load was applied by a vertical hydraulic piston. The hydraulic piston was positioned on a concrete slab that served as a loading plate. The lower box was driven by a horizontal hydraulic piston. The maximum horizontal displacement was 15 cm. A linear variable displacement transformer (LVDT) was connected between the fixed frame and the movable lower box to record the lateral displacement. A load cell was connected...
between the hydraulic piston and the steel frame of the lower box to measure the horizontal shear resistance force during each shear test. Another load cell was connected to the vertical piston and the loading plate to measure the vertical overburden force. The LVDT and the two load cells were connected to a data acquisition system to automatically record the displacement, the horizontal shear resistance force, and the vertical overburden force during each shear test.

![Large-scale direct shear test device](image)

**FIG 3. Large-scale direct shear test device**

**Test Program and Procedures**

*(1) Equipment verification using sand*

In order to verify that the large-scale shear device worked properly, control tests using sand were first conducted. To prevent the sand from falling out of the upper box when the two boxes were offset during the shearing, a 20 cm wide angle iron flange was bolted to the side of the lower box, as shown in Figure 4. The shear strength of sand was also tested on a standard direct shear machine according to ASTM D 3080-04 “Standard Test Methods for Direct Shear Test of Soils under Consolidated Drained Conditions,” using the same compaction and moisture content. The specimen dimensions on the standard direct shear machine were 5.9 cm in diameter and 4.5 cm in height. The standard shear testing of sand was done at two independent civil engineering consulting firms.

The test procedure of large-scale shear testing of sand is as follows:
(a) Align the lower and upper shear boxes and lock the lower shear box.
(b) Fill and compact sand in the lower box in three lifts to reach a target dry density of 1810 kg/m³. The sand was moistened at 4% water content to facilitate compaction.
(c) Fill and compact sand in the upper box the same way as in (b).
(d) Load a reinforced concrete slab on the sand in the upper box, and position the load cell and then hydraulic piston on the concrete slab. Power on the hydraulic ram to lower the piston to achieve the desired vertical pressure, and record the vertical deformation. The vertical pressure was maintained by the vertical hydraulic piston during the testing.
(e) Zero the readings of the horizontal load cell and the LVDT.
(f) Unlock the lower shear box, move the lower box at a constant displacement rate of 2.2 cm/min using the horizontal hydraulic piston. The horizontal resistance force, the horizontal displacement of the lower shear box, and the vertical force were automatically recorded by the data acquisition system. During the test, the vertical force fluctuated slightly and was maintained around the target value. The vertical forces were then averaged and the average was used in deriving the Mohr-Coulomb failure envelop.
(g) Notice the peak value of the horizontal force, and continue the test until the leveling-off of the shear resistance was observed.
(h) Terminate the shear test when the leveling-off of the shear resistance is observed or the maximum shear displacement of 18 cm is reached.
(i) Lift the vertical piston and release the vertical pressure, return the lower box back to its original position, and remove the material in the boxes.
(j) For each new shear test, the sand was removed and re-compacted.

FIG 4. Shear box configurations before and after shear test

Four vertical pressures were used: 24, 48, 96, and 144 kN/m² (or 500, 1000, 2000, and 3000 lb/ft²). For each normal load, the shear displacement vs. shear resistance force relationship was plotted; from the curve, the maximum shear force for each
normal load was derived. Then, the Mohr-Coulomb failure envelope was derived. Duplicate tests were conducted for each normal load to verify the reproducibility of the results.

(2) Shear testing of TDA on TDA

The shear testing of TDA followed the same procedure for the shear testing of sand. The TDA was compacted in three layers in each box, with a target density of 673 kg/m³ in each layer. Four vertical pressures were used: 24, 48, 96, and 144 kN/m² (or 500, 1000, 2000, and 3000 lb/ft²). Duplicate tests were conducted for each normal load to verify the reproducibility of the results. The TDA compressed significantly under the vertical loads and the density increased significantly under the four normal loads. The final densities after the application of vertical loads are listed in Table 1. Figure 5 shows the shear box positions in the front and back at the end of a test.

![Shear box positions in the front and back at the end of a shear test](image)

**FIG 5. Shear box positions in the front and back at the end of a shear test**

<table>
<thead>
<tr>
<th>Vertical Pressure (kN/m²)</th>
<th>0</th>
<th>24</th>
<th>48</th>
<th>96</th>
<th>144</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>673</td>
<td>807</td>
<td>1131</td>
<td>1352</td>
<td>1482</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSION**

(1) Equipment verification using sand

The Mohr-Coulomb failure envelopes of sand were derived from the large-scale shear testing. Duplicate tests were conducted. The results are shown in Figure 6. The test point at vertical normal pressure of 144 kPa did not align with the other points on a straight line. Although the test results for the 144 kPa normal pressure are repeatable, the authors deemed the test points for the 144 kPa normal pressure incorrect, because the Mohr-Coulomb failure envelop of sand should be linear. The
reason for the incorrect results could be at high vertical pressure, the horizontal piston that drove the shear box could not provide sufficient shear force. Therefore, the cohesion and internal friction angle were only based on the first three test points. The results from the large-scale shear tests and the standard direct shear tests are summarized in Table 2. The results showed that the large-scale shear tests provided comparable and slightly lower (conservative) value for internal friction angle and slightly higher (non-conservative) value for cohesion.

![FIG 6. Failure envelops of sand from large-scale shear testing](image)

**Table 2. Shear strengths of sand obtained from large-scale and standard direct shear tests.**

<table>
<thead>
<tr>
<th></th>
<th>Large-scale shear tests</th>
<th>Standard direct shear tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
</tr>
<tr>
<td>$c$ (kPa)</td>
<td>11.30</td>
<td>6.44</td>
</tr>
<tr>
<td>$\phi$ (deg)</td>
<td>36.5</td>
<td>39.5</td>
</tr>
<tr>
<td>Average $c$ (kPa)</td>
<td>8.87</td>
<td></td>
</tr>
<tr>
<td>Average $\phi$ (deg)</td>
<td>38.0</td>
<td></td>
</tr>
</tbody>
</table>

**2) Shear testing of TDA**

Figure 7 shows the shear failure envelopes of TDA. Duplicate tests were conducted and the results showed good repeatability. The failure envelopes were obtained from the shear stress vs. shear displacement relationships, which are shown in Figures 8 and 9. The four curves in each figure are labeled with their respective normal stresses. It is also noted that in Figure 7, the test point for 144 kPa normal stress did not align with the first three points on a straight line, as in the shear testing of sand in Figure 6. The shear resistance vs. displacement relationships in Figures 8 and 9 for the 144 kPa normal pressure also indicate the horizontal piston was not able to provide sufficient
horizontal shear force to push further the shear box, and the shear testing for that pressure had to be terminated earlier. Therefore, the test points for the normal pressure of 144 kPa were not considered in obtaining the Mohr-Coulomb envelop in Figure 7. Figure 7 revealed the average apparent cohesion of TDA is 14.3 kPa, the average internal friction angle of TDA is 36.1°. The apparent cohesion is due to the locking mechanism of TDA with TDA

![FIG 7. Failure envelopes of TDA](image)

![FIG 8. Shear stress vs. displacement relationships of TDA, test 1](image)
CONCLUSIONS

In this research, a large-scale direct shear test device was designed and constructed in order to obtain the shear resistance of TDA of large sizes. The shear device can accommodate specimens that are 79 cm wide, 80 cm long, and 122 cm tall; the maximum horizontal shear displacement is 18 cm, and the vertical pressure can be up to 144 kPa. The control tests using sand showed that the equipment obtained comparable and slightly conservative shear resistance. The shear testing concluded that TDA with sizes from 5 to 100 mm under an initial density of 673 kg/m$^3$ have apparent cohesion of 14.3 kPa and internal friction angle of 36.1°.

ACKNOWLEDGEMENTS

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REFERENCES


