



Tire Derived Aggregate for Underdrain Applications- Final Report

1. INTRODUCTION

Since 1990, VTrans and the Vermont Agency of Natural Resources (VANR) have had an interest in the repurposing of tire byproducts in transportation infrastructure, including the use of shredded whole scrap tires, known as Tire Derived Aggregate (TDA). Vermont’s universal recycling laws have made reliable quantities of material available, though a market for their use does not currently exist in Vermont. Instead, the approximately 700,000 scrap tires that Vermont generates per year are shipped out of state for processing and use [1]. These are mainly burned as Tire Derived Fuel (TDF) in paper mill boilers or cement kilns, with lesser amounts used for mulch, playground surfaces, and rubberized asphalt. VTrans is supporting the repurposing effort by researching methods to recycle and repurpose scrap tires. Since 1990 TDA has been used in several VTrans projects including a test side slope embankment in Middlesex, VT [2], a study on geotechnical properties of TDA [3], and documentation of 65,000 tires used as TDA in a capillary break layer beneath gravel roads in Georgia, VT [4][5].

The successful use of TDA as a geotechnical replacement material has been researched and documented nationally and in Vermont. In 2006, VTrans developed plans to test tire chips in blended aggregate to obtain a lightweight fill for abutment backfill. Literature also suggests that tire chips can function as a full replacement material for drainage backfill in subsurface drains with proper design and installation. The VTrans’ Research Section and Recycled Materials Working Group concluded through literature review and discussion that substituting TDA for aggregate in an underdrain would also be feasible. This project planned to investigate the performance, suitability, and practicality of using TDA as an aggregate replacement in underdrains, with a focus on its performance during installation and assessing potential environmental impact.

A full depth reconstruction project: Londonderry-Chester STP PS19(10), on VT 11 was chosen for the trial. VANR identified five regional sources of Type A TDA that would meet ASTM D6270 Standard Practice for Use of Scrap Tires in Civil Engineering Applications. This project targeted using TDA that meets the requirements in Special Provision – Draining Aggregate (Shredded Tires), see Appendix A. Type A TDA will have the parameters as shown in Table 1 [6]. TDA for the Londonderry-Chester project was ultimately acquired from BDS Waste Disposal in Norridgewock, Maine.

Table 1: Type A TDA Parameters

	Size (in/mm)	Max. Dimension in Any Direction (mm)	% Passing 100-mm Sieve (%)	% Passing 75-mm Sieve (%)	% Passing 4.75-mm Sieve (%)	100 Tire Passenger Tire Equivalent (PTE) Weight (TON)	100 Tire Passenger Tire Equivalents (PTE) Volume (CY)	In-Place Density (PCF)
Type A	3-4 in 75-100 mm	200	100	95 (minimum)	5 (maximum)	1	1.4	45-50

2. OBJECTIVE

The objective of this research project was to determine the effectiveness and appropriate application for TDA as a drainage medium in underdrains. The outcomes of interest in using TDA were (1) gauging constructability, (2) determining performance after installation, (3) assessing any environmental impacts, and (4) cost versus other drainage media. The VTrans Research Section and Recycled Materials Group have concluded that incorporating TDA as an underdrain material is a feasible technique to beneficially use recycled material in Vermont's transportation infrastructure. This research effort included the following four phases:

- 1) Observation and documentation of the construction;
- 2) Field observations comparing the TDA test section performance to the control section;
- 3) Field collection and laboratory analyses of water quality samples; and
- 4) Cost/benefit comparisons.

3. TEST SITE SUMMARIES

This section describes the Londonderry-Chester STP PS19-(10) demonstration project installed in Summer 2020, which was the 14.006-mile full depth reclamation of VT 11 starting in Londonderry at MM 1.952 and continuing to Chester MM 4.373. To better support the new roadway infrastructure additional underdrains were installed, including the TDA test sections. This was the first project using TDA for underdrain in Vermont. There are two locations where the underdrain was installed with TDA on this project: one in the Town of Andover and the other in the Town of Chester. The Chester TDA section is identified as "East Underdrain" and located between C142+40LT and 145+80LT. The Andover TDA section is identified as "West Underdrain" and located between stations A183+00RT and A186+10RT. The Londonderry-Chester project construction began November 1, 2019 and was completed July 1, 2021.

3.1. Andover – West Underdrain

The West Underdrain was constructed for a 310' section off the eastbound lane of VT 11, just east of the intersection of TH (37), Stigers Road, location shown in Figure 1. 43.27 CY of TDA was utilized. The installed underdrain was placed 15' from the centerline of the road and had an inlet elevation of 974.861', an outlet elevation of 967.641', and a correlating slope of 2.3%.

The West Underdrain is in a location that did not have previous underdrain. The trench excavation revealed sandy soils with clay fines and scattered cobbles. Groundwater was not intercepted to depth, and no mottling was observed in the soils. VTrans standard underdrain design was employed, with TDA substituting for ¾" stone aggregate. As part of standard underdrain design geotextile lining was placed in the excavated trench, on the bottom and sides, with width enough for a 1' overlap at the top, once piping and TDA were in place.



Figure 1: Location of Andover Test Section, VT-11

The TDA used in the Andover test section had wires protruding from the rubber. This may have impacted the probability of mobilizing iron due to the greater potential for water contact as water flows through the underdrain. The Special Provision *Drainage Aggregate (Shredded Tires)* stated that the TDA should follow ASTM D6270, Appendix B. This ASTM standard requires that TDA have less than 1% by weight of metal fragments that are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25mm from the cut edge of the TDA on 75% of the pieces by weight and no more than 50mm on 90% of the pieces by weight. Based on observation only, VTrans and VANR do not believe that the TDA used on this project met this specification.

It was noted that in some discrete areas of the off-site stockpile, the TDA was coated with fine grained soil, while TDA in other areas of the stockpile was free of soil. It appeared that the degree of “cleanliness” varied by incoming load as seen in Figure 2.

Photos of the material are available in Figure 2.



Sample TDA



TDA delivery



TDA Stockpile



Soiled TDA

Figure 2: Andover Materials used in test section

Construction took place on June 10, 2020. A trench was excavated and fabric was then laid in the trench and spiked into the trench walls to anchor in place. 6" of TDA was then placed inside the fabric and the 6" perforated drainage pipe was laid on top of the TDA bed. An additional 12" layer of TDA was placed over the drainage pipe. Compaction with a vibratory compactor was attempted, however, the TDA rebounded to its original volume, and compaction was abandoned. Fabric was then wrapped around the underdrain system. A 12" layer of soil was placed above the underdrain and the soil was compacted. VTrans Research and VANR staff were present for observation and written and photo documentation with assistance from VTrans Resident Engineers. The contractor noted no great installation advantages or disadvantages with TDA compared to crushed stone. Spreading and leveling the TDA is somewhat more difficult as the material does not lend itself to hand shoveling. The protruding steel wires remaining in the TDA also did adhere to some extent to the geotextile trench walls. Both issues were deemed minor by the contractor. The installation process can be seen in Figure 3.



Fabric placed in trench



Placing TDA in fabric



TDA placed over drainage pipe



Fabric wrapped over TDA



Soil compaction



Typical underdrain system with lightweight backfill used on project

Figure 3: Test Section Construction

3.2. Swett Rd, Chester – East Underdrain

The project installed 47.9 CY of TDA along 340 feet of the west side of VT-11 just south of Swett Road in Chester, location shown in Figure 6. There was no existing underdrain at the site. The installed underdrain was placed 16' from the centerline of the road and had an inlet elevation of 758.11', an outlet elevation of 741.10', and a correlating slope of 5%. The TDA used in this underdrain was the same material as that used for the Andover test section, as shown in Figure 2.



Figure 6: Location of Chester Test Section, VT-11.

Research staff were not on hand during construction of the East Underdrain on July 11, 2020, to observe and document construction practices and conditions. During excavation for the TDA underdrain, VTrans Resident Engineers reported no existing piping or drainage medium discovered, although groundwater flow into the inlet sleeve was commonly observed. The existing drainage structure at the outlet end of the reported underdrain only had an inlet sleeve. This drainage structure discharged through an 18" CMP culvert that went under VT 11 with an outlet into the Williams River. The structure is shown in Figure 7. Design of the 340' TDA underdrain was identical to conventional underdrains, that is, as shown on Figure 3, with the substitution of TDA for natural aggregate.



Figure 7: Drainage structure at Chester underdrain

4. COST BENEFIT

This is the first project in Vermont using TDA since the 1990s, therefore VTrans does not have significant data on the typical costs of TDA other than the four contractors who bid on this project. From these four bids, the average cost of TDA underdrain was \$37.62 per LF. The chosen contractor priced TDA underdrain at \$36.50 per LF. The typical aggregate underdrain item used on this project had an average bid price of \$24.94 per LF. The chosen contractor priced this item at \$21.00 per LF.

In this project, using TDA instead of typical aggregate, the underdrain costs \$15.50 more per LF, or an increase of 73.81%.

5. INSTALLATION CONCLUSIONS

Neither the contractor, VTrans Resident Engineers, nor VTrans Research and ANR staff noted appreciable constructability differences between TDA and conventional aggregate. TDA is more difficult to spread with hand tools, and the protruding wires tended to adhere to the geotextile filter fabric, but these were considered minor nuisances. Beneficially, TDA is less dense than crushed stone, allowing for transport in larger trucks or roll-off containers.

One minor hindrance to construction was difficulty with compaction. The vibratory compactor visibly bounced on the TDA. Additionally, the material did not seem to change in elevation after having been run over by the vibratory compactor. The VTrans Resident Engineers considered this a minimal issue and directed the contractor to continue on with underdrain construction after the TDA did not compact.

6. WATER QUALITY MONITORING

Based on data available regarding environment impacts of TDA when used in similar construction applications, and on the design and purpose of the underdrain, the VANR developed a water quality monitoring program designed to document preexisting water quality conditions of the groundwater and surface water and any water quality variations following construction of the TDA underdrain(s).

6.1. Approach

Establish Background Locations: The original project workplan, developed prior to selection of the Londonderry-Chester underdrain

locations, envisioned obtaining background water quality data with one, or a combination, of these methods:

- a. If the sites proposed for TDA underdrain had functioning underdrain(s), sample(s) of the preexisting underdrain discharge were to be collected and analyzed before construction;
- b. If during excavation of the new underdrain(s) any groundwater were encountered, sample(s) of the groundwater would be collected and analyzed; and
- c. If neither (a) nor (b), above, were feasible, and background groundwater quality was still desired, a temporary, upgradient monitoring well was to be installed by VTDEC. This installation was to occur prior to project initiation, in a suitable location within the right-of-way and in accordance with USEPA guidance "Design and Installation of Monitoring Wells" dated January 16, 2018.

The location of the proposed East Underdrain was believed to have had an existing underdrain, based on historic records and the existence of a drop inlet on the westbound shoulder. A visible inlet to the structure consistently carried water flow from what was presumed to be the existing underdrain. The drop inlet discharged into an 18" corrugated metal pipe passing under VT 11 with outflow into the Williams River (Figure 7). The outflow of the culvert was deemed to be representative of East Underdrain background water quality, and this sampling location was utilized for each subsequent sampling event after the TDA underdrain was constructed.

The site of proposed West Underdrain was not co-located with a preexisting underdrain. However, a groundwater seepage was present, and a small stream entered an existing culvert slightly west of the proposed West Underdrain location. These locations were considered representative of background water quality and sampled for background conditions.

Water Quality Sampling Events and Analysis: Water quality samples were collected by ANR staff on six occasions: prior to installation of the TDA underdrains, three weeks after installation, and four more occasions over the following year.

All water samples were field measured for pH, specific conductance, and temperature using an Accumet 85 meter, with pH being calibrated on the day of sampling. Additionally, a field measurement of estimated flow was taken by filling a container with a known capacity over a measured amount time, as practicable.

The suite of laboratory analyses selected for this work were based on previous studies of potential contaminants of concern associated with TDA and included:

- Total Dissolved Solids (TDS)
- Chemical Oxygen Demand (COD)
- Metals, Total and Dissolved (0.45-micron filter)
- manganese
- iron
- barium
- zinc
- lead
- sodium
- Hardness as CaCO₃
- Chloride
- Volatile Organic Compounds (VOCs) by EPA Method 8260C
- Semi-Volatile Organic Compounds (SVOCs) by EPA Method 8270

Inorganic parameters were analyzed by the Vermont Agency of Agricultural/Natural Resources Laboratory in Randolph Center, Vermont. Organic parameters, VOCs, and SVOCs, were analyzed by Endyne Inc., of Williston, Vermont.

Contingency for Sampling Expansion: The original project workplan included contingency sampling in the event that the analytical results of the TDA underdrain discharge indicated high concentrations of parameters, or parameters or concentrations markedly different than those previously cited in the literature. If this occurred, and there was evidence of impacts to ground or surface water above established standards, water samples were to be collected from an appropriate location at the nearest permanent surface water body, if feasible. Implementation of this expanded contingency plan, ultimately, was not necessary.

6.2. Water Quality Results

West Underdrain: During excavation no groundwater was observed at the location and while the underdrain was located at the base of a steep, wooded slope, there was no indication that groundwater was seasonally present at depth within the installation area. Therefore, no preexisting natural conditions background sample was able to be obtained from this location. A single sample was obtained from a stream contributing to a preexisting underdrain located immediately to the west of the installation area. The underdrain that this stream contributed to and where the sample was taken from, was visually impaired, with iron staining and bacterial growth. Following installation, Underdrain West does not appear to be collecting water, either from the subsurface or runoff from the VT 11 road surface, even after periods of prolonged rainfall. No samples have been obtained from this TDA underdrain system since installation.

East Underdrain: Samples were collected at the site in May 2020, July 2020, October 2020, April 2021, July 2021, and November 2021. Samples were sent to Endyne Inc. to be analyzed for Volatile Organic Compounds (VOC) and Semi Volatile Organic Compounds (SVOC) parameters. Samples were sent to the Vermont Agriculture and Environmental Laboratory (VAEL) to be analyzed for inorganic and indicator parameters. Through an interagency MOI agreement, VANR paid for testing at VAEL and VAOT paid for testing at Endyne Inc.

Flow: Discharge from the East Underdrain, through the 18" CMP, was low but relatively constant, varying at the times of sampling from 0.12 gallons per minute (GPM) to 1.3 GPM.

Specific conductance is utilized as an indirect measurement of dissolved inorganic substances in the water. Elevated or increasing conductivity could be indicative of a source of contamination. The conductivity of the East Underdrain water peaked with the first sample after installation of the TDA underdrain. This was very likely due to disturbance of soil during trench excavation, with some possible contribution from soil adhered to the surface of the TDA. By the final November 2021 sampling, specific conductance had declined to 77 $\mu\text{mhos/cm}$, at the low end of the range for naturally occurring ground or surface water. Within the overall trend of decreasing conductivity following installations slight fluctuations appear to reflect the relationship between conductivity and temperature (Figure 8).

pH of the discharge ranged from 6.00, slightly acidic, to 8.14, slightly basic. The highest pH was recorded in the first sample collected after the installation of the TDA underdrain. However, the pH declined to 6.62 and 6.43 respectively in

the subsequent sampling events, before a pH of 8.12 was measured in July 2021. No particular trend or cause for variability was observed (Figure 8).

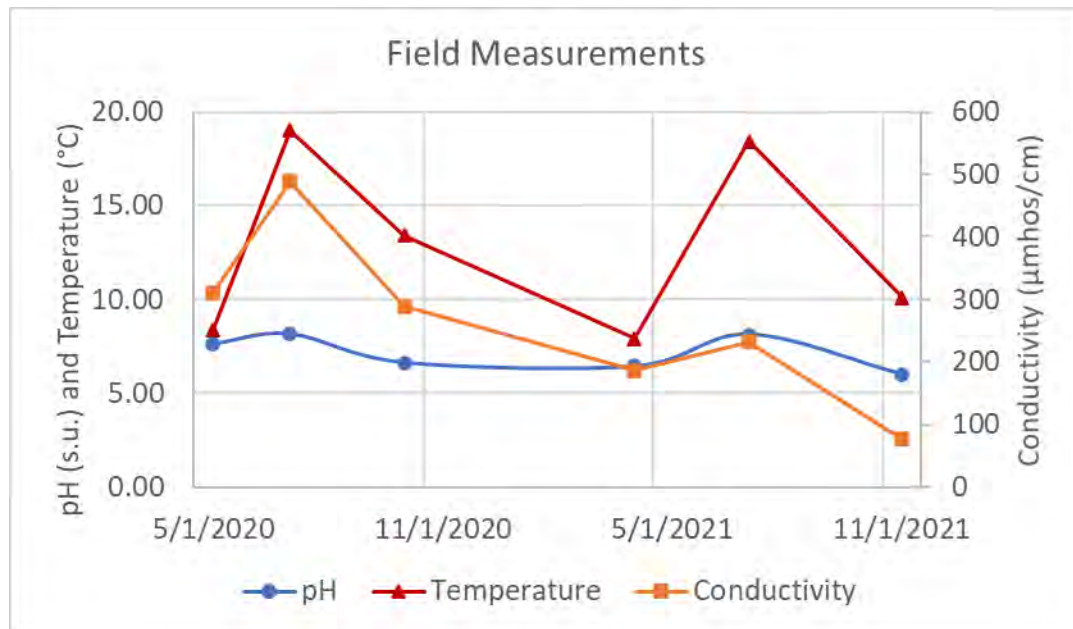


Figure 8: East Underdrain pH and Conductivity trends following installation.

Total Dissolved Solids (TDS) is another indicator parameter measuring the amount of inorganic chemicals dissolved in water, primarily metals, minerals, and salts, either naturally occurring or anthropogenic. Elevated TDS could denote a source of contamination. Groundwater TDS levels of less than 300 parts per million (ppm) are typical, and as a point of comparison, it is recommended that drinking water sources be investigated and/or treated when TDS exceeds 1,000 ppm. TDS concentrations within the East Underdrain ranged between 310-122 ppm, well within the range of naturally occurring Vermont groundwater.

Chemical Oxygen Demand (COD) is a measure of the organic matter content within a sample that is available to be biochemically decomposed. Uncontaminated groundwater, with little surface connections, will have little, if any, organic matter present. Uncontaminated surface water will contain some organic content from plants and animals living in the water, with a COD measurement generally less than 20 mg/l. COD from the East Underdrain had an average COD measurement of 25.8 mg/l. This is slightly higher than uncontaminated surface water and groundwater, but not unexpected as the underdrain is collecting roadside drainage and blends groundwater and infiltrated surface water and runoff.

Hardness as CaCO₃ – Hardness of water is caused by magnesium and calcium compounds, and is measured by the concentration of calcium carbonate (CaCO₃). Below 60 milligrams per liter (mg/l) of CaCO₃ is considered “soft” water. The average CaCO₃ concentration in East Underdrain water was 36.4 mg/l, with only the November 2021 sample being above 60 mg/l, at 94.5 mg/l. These concentrations are within the typical range for Vermont waters.

Volatile Organic Compounds (VOCs) and Semi-Volatile Organic Compounds (SVOCs) - VOCs and SVOC are organic chemicals that typically escape from surface water through volatilization, but tend to be persistent when dissolved in groundwater. They are common components in many household and industrial products and if found in the groundwater following TDA installation may be representative of the additives, residual oils, fuel range organics, and polynuclear aromatic hydrocarbons (PAHs) that may be present within the TDA. Over the six sample events, the suite of VOCs and SVOCs were all reported below method detection limits, with the exception of three compounds detected during the July 2020 sampling event, immediately following installation. The three compounds detected are reported within Table 2 below along with the applicable water quality criteria.

Table 2: Organic compounds detected at the East Underdrain

<i>Units: µg/L</i>	July 2020 detection
Acetone	240
4-Methyl 2-Pentanone (MIBK)	11.2
Aniline	9.9

The detection of the VOCs (acetone and 4-Methyl 2-pentanone or MIBK) and SVOC (aniline) only during the first sample event following installation of the TDA is likely related to the flushing of these compounds from the installed material with no indication of persistent leaching and/or a reflection of a shift in the oxidative/reductive conditions due to the installation. Aniline has been documented in the literature as leaching from tire shred [7]. Acetone and MIBK are utilized as industrial solvents and MIBK can be released to the environment in exhaust gas from vehicles.

Metals, Total and Dissolved - Total and dissolved (filtered through a 0.45-micron filter) metals samples were collected, in order to differentiate between metals that may be present in the sediment carried by the underdrain discharge (total) and those that could be attributed to leaching or desorbing from the TDA (dissolved).

The table presented in Appendix C summarizes the water quality analytical results for parameters that were reported to be present at concentrations above Laboratory Practical Quantitation Levels (PQLs). Shaded values highlight exceedances of either groundwater enforcement standards or a surface water quality criterion. The inorganic compounds detected in exceedance of Vermont available water quality standards (either groundwater or surface water) were iron, manganese and arsenic. It should be noted that these three compounds are commonly detected within Vermont groundwater and are particularly susceptible to being released from bedrock and sediments under reducing, limited oxygen, conditions. For each of these compounds, a portion of the total concentrations detected were attributed to the dissolved components, but there were also significant particulate (total) concentrations present in each sample.

Samples obtained in November 2021 were significantly elevated in all compounds analyzed when compared to all prior samples. It should be noted that flow rate was estimated to be only 0.14 gallons per minute and that drought conditions had been reported across much of Vermont for the preceding months. These conditions are believed to be reflective of that low flow rate and the water primarily being derived from roadside runoff rather than intercepted groundwater. This sudden increase in concentrations is not likely due to the underdrain installation, but the sampling period ended after this November sample was collected and it is impossible to comment upon potential recovery in quality.

Excluding these potentially anomalous November 2021 samples, the other sampling events did indicate a change in water quality conditions following installation of the East Underdrain. The background sample obtained in May of 2020, prior to installation of the TDA, is only a single sample point, but average total barium concentrations increased 53%, average dissolved calcium concentrations increased 77% and average dissolved nickel concentration increased 46% over the pre-installation sample concentration. The observed increases were all at their greatest concentrations immediately following installation of the underdrain and decreased with time. However, they did remain elevated relative to the pre-installation background conditions. This may reflect either the introduction of material with the installation of the TDA, either from the TDA or the coated sediment, or the general impacts of disturbance associated with the construction. In hindsight, sampling a control section to rule out this general disturbance associated with construction would have been helpful.

6.3. Water Quality Conclusions

Following installation of the East Underdrain, samples were able to be obtained allowing for a comparison of pre-and post- TDA installation water quality conditions. The Vermont groundwater enforcement standard, which is equivalent to Vermont drinking water standards was exceeded only for manganese and arsenic during two of the five sampling events. It should be noted that these compounds, similar to iron which exceeded Vermont surface water criteria, are commonly

found in high concentrations throughout Vermont, particularly where reducing conditions are present. Indicators of contamination were also present with the detection of organic compounds. However, these were only detected in the sampling event immediately following installation indicating that this impact may be of limited duration and were not in exceedance of any Vermont standards.

7. CONCLUSIONS

On an economic basis, in Vermont, TDA will likely not be cost competitive with conventional aggregate, and for that factor alone, it is unlikely that TDA will be used as a direct substitute for stone. The benefits of TDA are that it is light weight, vibration dampening, and has insulative properties. In transportation design applications where these properties are required, TDA could be a cost-effective alternative to conventional materials.

While there was some indication of short-term impact on water quality, there was no ongoing exceedance of Vermont surface water quality criteria or groundwater quality standards that indicate that the TDA installation has not resulted in significant health or environmental risks. It is likely that additional projects utilizing TDA would similarly have no harmful impact, provided specifications, design and construction methods are developed with consideration of environmental impact. Although TDA is not currently cost competitive with conventional aggregate, it does prove a viable reuse alternative.

At the project's end of life, we expect that cleanly excavated TDA can be used on another project. If it is not usable, then the used TDA needs to be managed as a waste.

8. REFERENCES

- [1] Report to the Vermont Legislature on Problem Scrap Tire Piles. Rep. Solid Waste Management Program Department of Environmental Conservation Vermont Agency of Natural Resources, 8 Jan. 2013. Web. Access 27 Jan. 2022. <https://dec.vermont.gov/sites/dec/files/wmp/SolidWaste/Documents/ScrapTireReportLegJan13.pdf>
- [2] Winters, P. (1991). *Use of Tire Chips in a Highway Embankment*. Report 91-5, April 1991. Vermont Agency of Transportation, Materials and Research Section. [https://resources.vtrans.vermont.gov/documents/archivedresearch/U1991%20-%2005%20\(OCR\)%20Use%20of%20Tire%20Chips%20in%20a%20Highway%20Embankment.pdf](https://resources.vtrans.vermont.gov/documents/archivedresearch/U1991%20-%2005%20(OCR)%20Use%20of%20Tire%20Chips%20in%20a%20Highway%20Embankment.pdf)
- [3] Benda, C. C. (1995). *Engineering Properties of Scrap Tires Used in Geotechnical Applications*. Report 95-1, February 1995. Vermont Agency of Transportation, Materials and Research Section. [https://resources.vtrans.vermont.gov/documents/archivedresearch/1995%20-%2001%20\(OCR\)%20Engineering%20Properties%20of%20Scrap%20Tires%20Used%20in%20Geotechnical%20Applications.pdf](https://resources.vtrans.vermont.gov/documents/archivedresearch/1995%20-%2001%20(OCR)%20Engineering%20Properties%20of%20Scrap%20Tires%20Used%20in%20Geotechnical%20Applications.pdf)
- [4] Frascoia, R. I., & Cauley, R. F. (1994). *Tire Chips in the Base Course of a Local Road*. Interim Report 94-2, March 1994. Vermont Agency of Transportation, Materials and Research Division. [https://resources.vtrans.vermont.gov/documents/archivedresearch/1994%20-%2002%20\(OCR\)%20Tire%20Chips%20in%20the%20Base%20Course%20of%20a%20Local%20Road.pdf](https://resources.vtrans.vermont.gov/documents/archivedresearch/1994%20-%2002%20(OCR)%20Tire%20Chips%20in%20the%20Base%20Course%20of%20a%20Local%20Road.pdf)
- [5] Ashworth, L. (2002). *Tire Chips in the Base Course of a Local Road*. Final Report 2002-3, August 2002. Vermont Agency of Transportation, Materials and Research Section.

[https://resources.vtrans.vermont.gov/documents/archivedresearch/U2002%20-%2003%20\(OCR\)%20Tire%20Chips%20in%20the%20Base%20Course%20of%20a%20Local%20Road.pdf](https://resources.vtrans.vermont.gov/documents/archivedresearch/U2002%20-%2003%20(OCR)%20Tire%20Chips%20in%20the%20Base%20Course%20of%20a%20Local%20Road.pdf)

- [6] CalRecycle (2015). *Tire Derived Aggregate (TDA) – Type A and Type B Material Specification*. California Department of Resources Recycling and Recovery. <https://www2.calrecycle.ca.gov/Docs/Web/115371>
- [7] Duda, A., Kida, M., Ziembowicz S., Koszelnik, P. (2020). *Application of material from used car tyres in geotechnics – an environmental impact analysis*. Peer Life and Environment Journal. Access 13 April 2022. <https://peerj.com/articles/9546/>

Appendix A: TDA Special Provision

DRAINAGE AGGREGATE (SHREDDED TIRES)

- 45. DESCRIPTION. The work shall consist of constructing drainage systems using underdrains, underdrain outlets, flushing basins, and risers.

There is one underdrain location in Andover at station A 183+00 to A 185+96 and one underdrain location in Chester at station C 142+00 to C 145+80 that will be installing 6" underdrain utilizing Tire Derived Aggregate (TDA). These locations are experimental sections and require Vermont Agency of Natural Resources-Department of Environmental Conservation (ANR-DEC) to be on-site during construction to observe and document the installation. This monitoring will be paid for separately and is not included in the contract. The contractor shall notify the engineer 10 business days prior to this underdrain being installed so that ANR-DEC can be on-site during the installation of the underdrain with TDA. **This sentence deleted.** The ANR-DEC will be monitoring these installations during each quarter of the 2020 construction season with additional monitoring in 2021 and 2022. All construction observation and monitoring will be paid for separately and is not included in the contract.

- 46. MATERIALS. Materials shall meet the requirements of the following subsections:

Corrugated Polyethylene Pipe.....	710.03
Polyvinyl Chloride (PVC) Plastic Pipe.....	710.06
Corrugated Steel Pipe, Pipe Arches and Underdrains.....	711.01
Corrugated Aluminum Alloy Pipe, Pipe Arches, and Underdrains.....	711.02
Gray Iron Castings.....	715.01(b)

A Type A Certification shall be furnished for each of the materials listed above.

Drainage Aggregate (Shredded Tires) shall be a Type A Tire Derived Aggregate (TDA) in accordance with ASTM D6270. TDA shall not be contaminated by petroleum hydrocarbons, including but not limited to; oil, grease, gasoline, and diesel fuel as determined in accordance with EPA Method 8015. TDA shall not exceed the regulatory levels of metals contained in 40 CFR § 261.24 Table 1 - Maximum Concentration of Contaminants for the Toxicity Characteristic (D004 Arsenic, D005 Barium, D006 Cadmium, D007 Chromium, D008 Lead, D009 Mercury, D010 Selenium, D011 Silver) as determined in accordance with EPA Method 1311.

A Type D Certification shall be furnished with a Certificate of Analysis demonstrating the following:

- (a) A gradation in accordance with ASTM D6270 for Type A TDA.
- (b) TDA contains less than 1% (by weight) metal fragments in accordance with ASTM D6270.
- (c) TDA is free of contaminates in accordance with EPA Method 8015.
- (d) TDA does not exceed the regulatory levels of metals in accordance with EPA Method 1311.

47. INSTALLATION. Installation shall meet the requirements of Section 605 Underdrains.

48. AVAILABLE SUPPLIERS. As of February 2019, known Northeastern sources of Type A tire shreds are listed below. Other sources may also be available.

- 1. Lakin Tire, West Haven, CT, Attn: David Greenstein, (203) 932-5801
- 2. Geiter Done Demolition and Disposal, Buffalo, NY, Attn: Mike Honer, (716) 895-8121
- 3. FBS Tire Recycling, Inc., Littleton, MA, (978) 772-4251
- 4. BDS Waste Disposal, Inc., Norridgewock, ME, (207) 278-3833
- 5. Bob's Tire, New Bedford, MA. Attn: Aaron Bates, (508) 294-1781

49. METHOD OF MEASUREMENT. The quantity of Special Provision (Underdrain With Tire Derived Aggregate) to be measured for payment will be the number of linear feet installed in the complete and accepted work.

50. BASIS OF PAYMENT. The accepted quantity of Special Provision (Underdrain With Tire Derived Aggregate) will be paid for at the Contract unit price per linear foot.

Payment will be full compensation for fabricating, furnishing, transporting, handling, and placing the material specified, including coupling bands and fittings, tire derived aggregate, geotextile fabric, and for furnishing of all labor, tools, equipment, and incidentals necessary to complete the work.

Excavation will be paid for as Trench Excavation.

Payment will be made under:

<u>Pay Item</u>	<u>Pay Unit</u>
900.640 Special Provision (Underdrain With Tire Derived Aggregate)	Linear Foot

51. Deleted with Addendum #1.

52. Deleted with Addendum #1.

Appendix B: ASTM D6270



Designation: D6270 – 20

Standard Practice for Use of Scrap Tires in Civil Engineering Applications¹

This standard is issued under the fixed designation D6270; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reappraisal. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reappraisal.

1. Scope

1.1 This practice provides guidance for testing the physical properties, design considerations, construction practices, and leachate generation potential of processed or whole scrap tires in lieu of conventional civil engineering materials, such as stone, gravel, soil, sand, lightweight aggregate, or other fill materials.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*²

C127 Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate

C136/C136M Test Method for Sieve Analysis of Fine and Coarse Aggregates

D698 Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³))

D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³))

D1566 Terminology Relating to Rubber

D2434 Test Method for Permeability of Granular Soils (Constant Head)

D2974 Test Methods for Determining the Water (Moisture

Content, Ash Content, and Organic Material of Peat and Other Organic Soils

D3080/D3080M Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions (Withdrawn 2020)³

D4253 Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table

D5681 Terminology for Waste and Waste Management

D7760 Test Method for Measurement of Hydraulic Conductivity of Materials Derived from Scrap Tires Using a Rigid Wall Permeameter

F538 Terminology Relating to the Characteristics and Performance of Tires

2.2 *American Association of State Highway and Transportation Officials Standards:*

T 274 Standard Method of Test for Resilient Modulus of Subgrade Soils⁴

M 288 Standard Specification for Geotextiles⁵

2.3 *U.S. Environmental Protection Agency Standard:*

Method 1311 Toxicity Characteristics Leaching Procedure⁶

3. Terminology

3.1 *Definitions*—For definitions of common terms used in this practice, refer to Terminologies **D5681** (waste management), **F538** (tires), and **D1566** (rubber), respectively.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *bead wire, n*—a high-tensile steel wire surrounded by rubber, which forms the bead of a tire that provides a firm contact to the rim.

3.2.2 *casing, n*—the tire structure not including the tread portion of the tire.

3.2.3 *mineral soil, n*—soil containing less than 5 % organic matter as determined by a loss on ignition test. (**D2974**)

¹ This practice is under the jurisdiction of ASTM Committee D34 on Waste Management and is the direct responsibility of Subcommittee D34.03 on Treatment, Recovery and Reuse.

Current edition approved Sept. 1, 2020. Published September 2020. Originally approved in 1998. Last previous edition approved in 2017 as D6270 – 17. DOI: 10.1520/D6270-20.

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

³ The last approved version of this historical standard is referenced on www.astm.org.

⁴ *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part II: Methods of Sampling and Testing*, American Association of State Highway and Transportation Officials, Washington, DC.

⁵ *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part I: Specifications*, American Association of State Highway and Transportation Officials, Washington, DC.

⁶ *Test Methods for Evaluating Solid Waste: Physical/Chemical Methods*, 3rd ed., Report No. EPA 530/SW-846, U.S. Environmental Protection Agency, Washington, DC.

3.2.4 *preliminary remediation goal, n*—risk-based concentrations that the USEPA considers to be protective for lifetime exposure to humans.

3.2.5 *rough shred, n*—a piece of a shredded tire that is larger than 50 by 50 by 50 mm, but smaller than 762 by 50 by 100 mm.

3.2.6 *rubber buffings, n*—vulcanized rubber usually obtained from a worn or used tire in the process of removing the old tread in preparation for retreading.

3.2.7 *rubber fines, n*—small particles of ground rubber that result as a by-product of producing shredded rubber.

3.2.8 *scrap tire, n*—a pneumatic rubber tire discarded because it no longer has value as a new tire, but can be either reused and processed for similar applications as new or processed for other applications not associated with its originally intended use.

3.2.9 *steel belt, n*—rubber-coated steel cords that run diagonally under the tread of steel radial tires and extend across the tire approximately the width of the tread.

3.2.10 *tire chips, n*—pieces of scrap tires that have a basic geometrical shape and are generally between 12 and 50 mm in size and have most of the wire removed.

3.2.11 *tire-derived aggregate (TDA), n*—pieces of scrap tires that have a basic geometrical shape and are generally between 12 and 305 mm in size and are intended for use in civil engineering applications.

3.2.12 *waste tire, n*—a tire that is no longer capable of being used for its original purpose, but has been disposed of in such a manner that it cannot be used for any other purpose.

3.2.13 *whole tire, n*—a tire that has been removed from a rim but has not been processed.

4. Significance and Use

4.1 This practice is intended for use of scrap tires including: tire-derived aggregate (TDA) comprised of pieces of scrap tires, TDA/soil mixtures, tire sidewalls, and whole scrap tires in civil engineering applications. This includes use of TDA and TDA/soil mixtures as lightweight embankment fill; lightweight retaining wall backfill; drainage layers for roads, landfills, and other applications; thermal insulation to limit frost penetration beneath roads; insulating backfill to limit heat loss from buildings; vibration damping layers for rail lines; and replacement for soil or rock in other fill applications. Use of whole scrap tires and tire sidewalls includes construction of retaining walls, drainage culverts, road-base reinforcement, and erosion protection, as well as use as fill when whole tires have been compressed into bales. It is the responsibility of the design engineer to determine the appropriateness of using scrap tires in a particular application and to select applicable tests and specifications to facilitate construction and environmental protection. This practice is intended to encourage wider utilization of scrap tires in civil engineering applications.

4.2 Three TDA fills with thicknesses in excess of 7 m have experienced a serious heating reaction. However, more than 100 fills with a thickness less than 3 m have been constructed

with no evidence of a deleterious heating reaction (1).⁷ Guidelines have been developed to minimize internal heating of TDA fills (2) as discussed in 6.11. The guidelines are applicable to fills less than 3 m thick. Thus, this practice should be applied only to TDA fills less than 3 m thick.

5. Material Characterization

5.1 The specific gravity and water absorption capacity of TDA should be determined in accordance with Test Method C127. However, the specific gravity of TDA is less than half the value obtained for common earthen coarse aggregate, so it is permissible to use a minimum weight of test sample that is half of the specified value. The particle density or density of solids of TDA (ρ_s) may be determined from the apparent specific gravity using the following equation:

$$\rho_s = S_a(\rho_w) \tag{1}$$

where:

S_a = apparent specific gravity, and
 ρ_w = density of water.

5.2 The gradation of TDA should be determined in accordance with Test Method C136/C136M. However, the specific gravity of TDA is less than half the values obtained for common earthen materials, so it is permissible to use a minimum weight of test sample that is half of the specified value.

5.3 The laboratory-compacted dry density (or bulk density) of TDA and TDA/soil mixtures with less than 30 % retained on the 19.0-mm sieve can be determined in accordance with Test Methods D698 or D1557. However, TDA and TDA/soil mixtures used for civil engineering applications almost always have more than 30 % retained on the 19.0-mm sieve, so these methods generally are not applicable. A larger compaction mold should be used to accommodate the larger size of the TDA. The sizes of typical compaction molds are summarized in Table 1. The larger mold requires that the number of layers, or the number of blows of the rammer per layer, or both, be increased to produce the desired compactive energy per unit volume. Compactive energies ranging from 60 % of Test Methods D698 (60 % \times 600 kN-m/m³ = 360 kN-m/m³) to 100 % of Test Methods D1557 (2700 kN-m/m³) have been used. Compaction energy has only a small effect on the resulting dry density (3); thus, for most applications it is permissible to use a compactive energy equivalent to 60 % of Test Methods D698. To achieve this energy with a mold

⁷ The boldface numbers in parentheses refer to the list of references at the end of this standard.

TABLE 1 Size of Compaction Molds Used to Determine Dry Density of TDA

Maximum Particle Size (mm)	Mold Diameter (mm)	Mold Volume (m ³)	Reference
75	254	0.0125	(3)
75	305	0.0146	(4)
51	203 and 305	N.R. ^A	(5)

^A N.R. = not reported.

volume of 0.0125 m³ would require that the sample be compacted in five layers with 44 blows per layer with a 44.5 N rammer falling 457 mm. The water content of the sample has only a small effect on the compacted dry density (3) so it is permissible to perform compaction tests on air or oven-dried samples.

5.3.1 The dry densities for TDA loosely dumped into a compaction mold and TDA compacted by vibratory methods (similar to Test Methods D4253) are about the same (4-6). Thus, vibratory compaction of TDA in the laboratory (see Test Methods D4253) should not be used.

5.3.2 When estimating an in-place density for use in design, the compression of a TDA layer under its own self-weight and under the weight of any overlying material must be considered. The dry density determined as discussed in 5.3 are uncompresses values. In addition, short-term time-dependent settlement of TDA should be accounted for when estimating the final in-place density (7).

5.3.3 Values of the secant constrained modulus, M_{sec} , which vary linearly with the compacted unit weight and applied vertical stress, can be estimated as (8):

$$M_{sec} = 1.8\sigma_v + 115\gamma - 458 \text{ kPa} \quad (2)$$

where:

σ_v = vertical stress, and

γ = compacted unit weight, kN/m³.

5.3.4 Time-dependent settlement for an average duration of four weeks, ΔH_t , can be calculated as (9):

$$\Delta H_t = HC_{ac} \log \frac{t_1}{t_2} \quad (3)$$

where:

C_{ac} = modified secondary compression index ≈ 0.0065 for 100 % TDA,

H = thickness of the TDA layer,

t_1 = time when time-dependent compression begins (assumed to be one day), and

t_2 = time at which the magnitude of time-dependent compression is required.

For long-term settlement, refer to X1.11.

5.4 The compressibility of TDA and TDA/soil mixtures can be measured by placing TDA in a rigid cylinder with a diameter several times greater than the largest particle size and then measuring the vertical strain caused by an increasing vertical stress. If it is desired to calculate the coefficient of lateral earth pressure at rest K_0 , the cylinder can be instrumented to measure the horizontal stress of the TDA acting on the wall of the cylinder.

5.4.1 The high compressibility of TDA necessitates the use of a relatively thick sample. In general, the ratio of the initial specimen thickness to sample diameter should be greater than one. This leads to concerns that a significant portion of the applied vertical stress could be transferred to the walls of the cylinder by friction. If the stress transferred to the walls of the cylinder is not accounted for, the compressibility of the TDA will be underestimated. For all compressibility tests, the inside of the container should be lubricated to reduce the portion of the applied load that is transmitted by side friction from the sample to the walls of the cylinder. For testing where a high level of accuracy is desired, the vertical stress at the top and the bottom of the sample should be measured so that the average

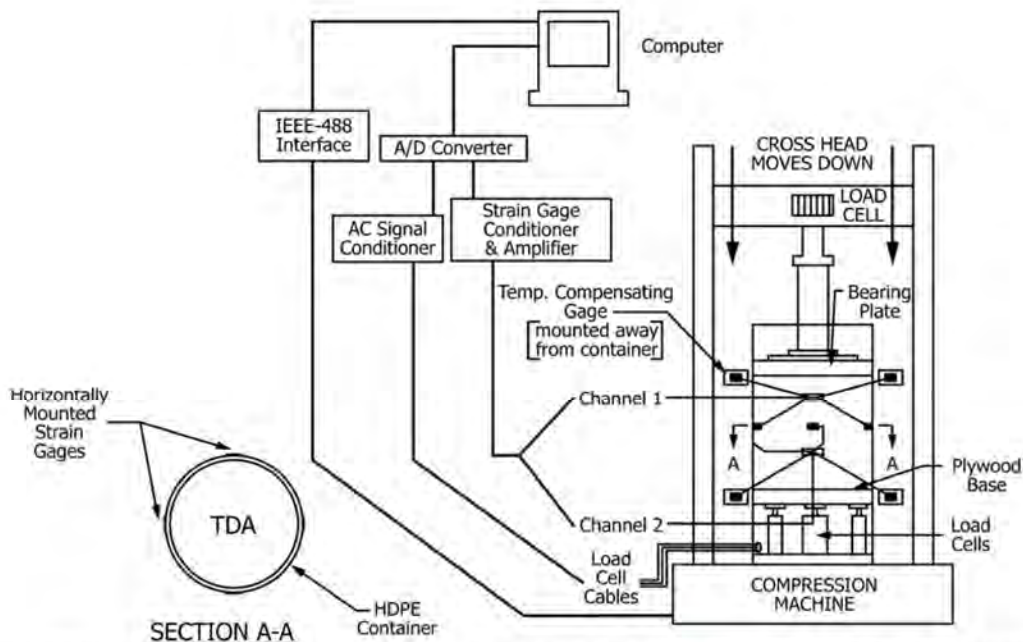


FIG. 1 Compressibility Apparatus for TDA Designed to Measure Lateral Stress and the Portion of the Vertical Load Transferred by Friction from TDA to Container (11)

vertical stress in the sample can be computed. A test apparatus designed for this purpose is illustrated in Fig. 1 (10).

5.5 The resilient modulus (M_R) of subgrade soils can be expressed as:

$$M_R = A\theta^B \quad (4)$$

where:

θ = first invariant of stress (sum of the three principal stresses),

A = experimentally determined parameter, and

B = experimentally determined parameter.

5.5.1 Tests for the parameters A and B can be conducted according to AASHTO T 274. The maximum particle size typically is limited to 19 mm by the testing apparatus, which precludes the general applicability of this procedure to the larger size TDA typically used for civil engineering applications.

5.6 The coefficient of lateral earth pressure at rest K_0 and Poisson's ratio μ can be determined from the results of confined compression tests where the horizontal stresses were measured. A test apparatus designed for this purpose is shown in Fig. 1. K_0 and μ are calculated from:

$$K_0 = \frac{\sigma_h}{\sigma_v} \quad (5)$$

$$\mu = \frac{K_0}{(1 + K_0)} \quad (6)$$

where:

σ_h = measured horizontal stress, and

σ_v = measured vertical stress.

5.7 The shear strength of TDA may be determined in a direct shear apparatus in accordance with Test Method D3080/

D3080M or using a triaxial shear apparatus. The large size of TDA typically used for civil engineering applications requires that specimen sizes be several times greater than used for common soils. Because of the limited availability of large triaxial shear apparatus, this method is generally restricted to TDA 25 mm in size and smaller. The interface strength between TDA and geomembrane can be measured in a large-scale direct shear test apparatus (12, 13).

5.8 The hydraulic conductivity (permeability) of TDA and TDA/soils mixtures should be measured with a constant head permeameter with a diameter several times greater than the maximum particle size. TDA with a maximum size smaller than 19 mm can be determined in accordance with Test Method D2434. However, TDA and TDA/soil mixtures used for civil engineering applications almost always have a majority of their particles larger than 19 mm, so this method is generally not applicable. Samples should be tested at a void ratio comparable to the value expected in the field. This may require a permeameter capable of applying a vertical stress to the sample to simulate the compression that would occur under the weight of overlying material. The high hydraulic conductivity of TDA should be accounted for in design of the permeameter. This includes provisions for an adequate supply of water and measuring the head loss across the sample using standpipes mounted on the body of the permeameter. An apparatus that takes these factors into account is shown in Fig. 2 (11). A standard test method for measurement of hydraulic conductivity of TDA is provided in Test Method D7760.

5.9 The thermal conductivity of TDA is significantly lower than for common soils. For TDA smaller than 25 mm in size, the thermal conductivity can be measured using commercially available guarded hot plate apparatus. For TDA larger than

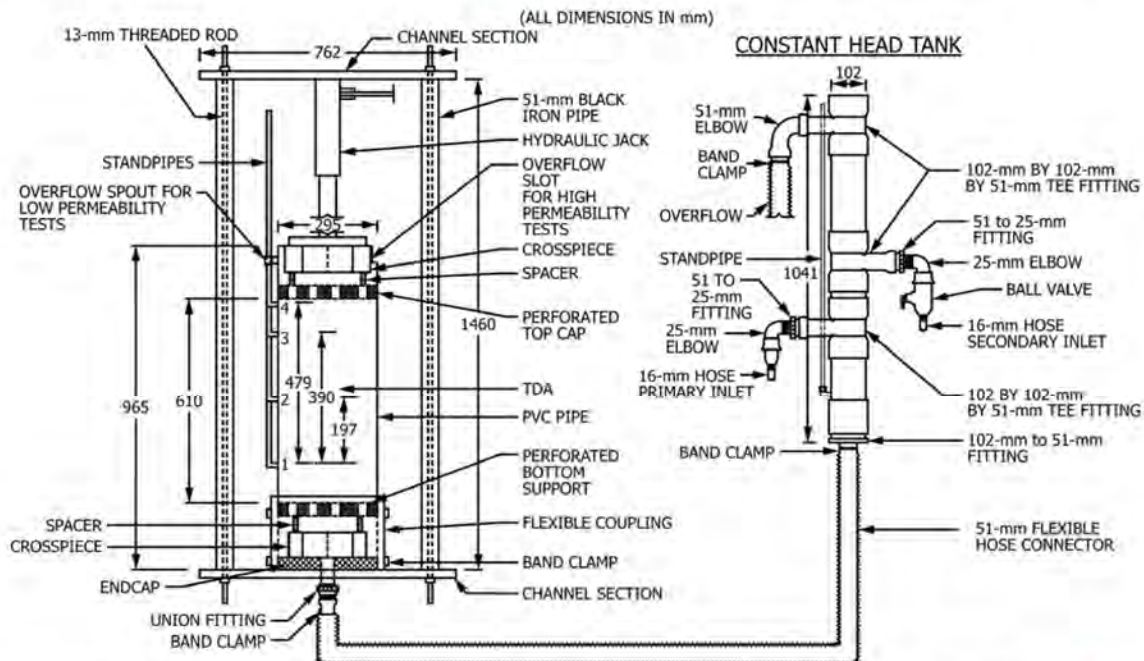


FIG. 2 Hydraulic Conductivity Apparatus for TDA with Provisions for Application of Vertical Stress (14)

25 mm, it is necessary to construct a large-scale hot plate apparatus (15). The thermal conductivity of TDA also can be back-calculated from field measurements (15).

6. Construction Practices

6.1 TDA have a compacted dry density that is one third to one half of the compacted dry density of typical soil. This makes them an attractive lightweight fill for embankments constructed on weak, compressible soils where slope stability or excessive settlement are a concern, as well as landslide repair.

6.2 The thermal resistivity of TDA is approximately eight times greater than for typical granular soil. For this reason, TDA can be used as a 150 to 450-mm thick insulating layer to limit the depth of frost penetration beneath roads. This reduces frost heave in the winter and improves subgrade support during the spring thaw. In addition, TDA can be used as backfill around basements to limit heat lost through basement walls, thereby reducing heating costs.

6.3 The low compacted dry density, high hydraulic conductivity, and low thermal conductivity make TDA very attractive for use as retaining wall backfill. Lateral earth pressures for TDA backfill can be about 50 % of values obtained for soil backfill (7, 10, 12). TDA can also be used as backfill for geosynthetic-reinforced retaining walls. An at-rest value of $K_0 = 0.3$ has been recommended for the design of cantilever retaining walls with TDA backfill up to 3 m thick (8, 16-18).

6.4 The hydraulic conductivity of TDA makes them suitable for many drainage applications including French drains, drainage layers in landfill liner and cover systems, and leach fields for on-site sewage disposal systems. For applications with a vertical stress less than 50 kPa, the hydraulic conductivity of TDA is generally greater than 1 cm/s, which is comparable to conventional uniformly graded aggregate. When TDA is used as a component of landfill leachate collection and removal systems, and other applications where the vertical stress would be greater than 50 kPa, the hydraulic conductivity and void ratio under the final design vertical stress should be considered. The hydraulic conductivity must meet applicable regulatory requirements and the void ratio must be sufficient to minimize clogging.

6.4.1 TDA can be used as a substitute for gravel in landfill horizontal gas collection trenches. In this application, 152 mm of TDA is placed on the bottom of the trench as a base material for the gas collection pipe. After the pipe is in place, an additional 305 mm of TDA is placed over the pipe (19).

6.5 TDA can be used as a vibration damping layer beneath rail lines to reduce the impact of ground-borne vibrations above 16 Hz on residences and businesses adjoining the tracks. In this application, a 300-mm thick layer of 75-mm maximum size TDA wrapped in filter fabric is placed beneath the conventional ballast/subballast system (20-23).

6.6 Two different sizes of TDA are commonly used for the applications discussed above. One has a maximum size of 75 mm and the other has a maximum size of 300 mm. Rough shreds can also be used for some applications, provided all tires

are shredded such that the largest shred is the lesser of one quarter circle in shape or 600 mm in length. In all cases, at least one side wall should be severed from the tread.

6.7 TDA with a maximum size of 75 mm or 300 mm are generally placed in 300-mm thick lifts and compacted by a tracked bulldozer, sheepsfoot roller, or smooth drum vibratory roller with a minimum operating weight of 90 kN. Rough shreds are generally placed in 900-mm thick lifts and compacted by a tracked bulldozer. For most applications, a minimum of six passes of the compaction equipment should be used.

6.8 TDA should be covered with a sufficient thickness of soil to limit deflections of overlying pavement caused by traffic loading. Soil cover thicknesses as low as 0.8 m may be suitable for paved roads with light traffic. For paved roads with heavy traffic, 1 to 2 m of soil cover may be required. For unpaved applications, 0.3 to 0.5 m of soil cover may be suitable depending on the traffic loading. The designer should assess the actual thickness of soil cover needed based on the loading conditions, TDA layer thickness, pavement thickness, and other conditions as appropriate for a particular project. Regardless of the application, the TDA should be covered in such a way as to prevent contact between the public and the TDA, which may have exposed steel belts.

6.9 In applications where pavement will be placed over the TDA layer, highway drainage applications, and retaining wall backfill, the TDA layer should be completely wrapped in a layer of geotextile to minimize infiltration of soil particles into the voids between the TDA. AASHTO M 288 should be used for guidance on geotextile selection.

6.10 Whole scrap tires and tire sidewalls that have been cut from the tire casing can be used to construct retaining walls, reinforcing mats beneath roads constructed on weak ground, and erosion protection layers.

6.11 TDA fills should be designed to minimize the possibility of an internal heating reaction (2). Oxidation of the exposed wire is the primary mechanism for an exothermic reaction responsible for self-heating in TDA (24). Conditions favorable for oxidation of exposed steel or rubber, or both, include: retention of heat caused by the high insulating value of TDA in combination with a large fill thickness; large amounts of exposed steel belts; and smaller TDA sizes and excessive amounts of granulated rubber particles.

6.11.1 TDA layers of greater than 3 m vertical thickness are not recommended. A 3-m TDA fill which is constructed based on current design guidelines should not experience an exothermic reaction resulting in self-heating that leads to combustion (24). Design of fills that are mixtures or alternating layers of TDA and soil should be handled on a case-by-case basis.

6.11.2 Fills shall be constructed in such a way that there shall be no direct contact between TDA and organic matter. One possible way to accomplish this is to cover the top and sides of the fill with a 0.5-m thick layer of compacted soil. The soil should be separated from the TDA with a geotextile fabric. Additional fill may be placed on top of the soil layer as needed to meet the overall design of the project. There is no need to try

to exclude water or air movement in an effort to reduce the risk of a hazardous level of self-heating (24).

6.11.3 Embankments constructed in accordance with the guidelines have shown no evidence of self-heating (25).

6.12 Type A TDA is a suitable alternative substitute for rock aggregate in on-site septic systems in regard to wastewater treatment and media durability (26).

7. Material Specifications

7.1 The material specifications for TDA that are presented below take into consideration the need to limit internal heating of TDA fills as discussed in 6.11, producing a material that can be placed and compacted with conventional construction equipment, and limiting exposed steel belts to allow for rubber-to-rubber contacts between the pieces when placed in a fill. Moreover, TDA meeting the specifications can be produced with reasonably well-maintained processing equipment that has been properly selected for the size product being produced. Specifications are provided for two size ranges. The first is termed Type A and is suitable for many drainage, vibration damping, and insulation applications. The second is larger and is termed Type B. It is suitable for use as lightweight embankment fill, wall backfill, and some landfill drainage and gas collection applications.

7.1.1 The TDA shall be made from scrap tires which shall be shredded into the sizes specified in 7.1.3 for Type A TDA or 7.1.4 for Type B TDA. They shall be produced by a shearing process. TDA produced by a hammer mill will not be allowed. The TDA shall be free of all contaminants including but not limited to oil, grease, gasoline, and diesel fuel that could leach into the groundwater or create a fire hazard. In no case shall the TDA contain the remains of tires that have been subjected to a fire, because the heat of a fire may liberate liquid petroleum products from the tire that could create a fire hazard when the TDA are placed in a fill. The TDA shall be free from organic matter such as fragments of wood, wood chips, topsoil, etc.

7.1.2 The TDA shall have less than 1 % (by weight) of metal fragments that are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the TDA on 75 % of the pieces (by weight) and no more than 50 mm on 90 % of the pieces (by weight). The gradation shall be measured in accordance with Test Method C136/C136M, except that the minimum sample size shall be 6 to 12 kg for Type A TDA and 16 to 23 kg for Type B TDA.

7.1.3 Type A TDA shall have a maximum dimension, measured in any direction, of 250 mm. In addition, Type A TDA shall have 100 % passing the 100-mm square mesh sieve, a minimum of 95 % passing (by weight) the 75-mm square mesh sieve, a maximum of 70 % passing (by weight) the 38-mm square mesh sieve, and a maximum of 5 % passing (by weight) the 4.75-mm sieve, as summarized in Table 2.

7.1.4 Type B TDA shall have a maximum of 16 % (by weight) with a maximum dimension, measured in any direction, of 300 mm and 100 % with a maximum dimension, measured in any direction, of 450 mm. At least one side wall shall be removed from the tread of each tire. The side wall will be considered removed if the bead wire has been completely

TABLE 2 TDA Gradation Requirements (27)

Sieve Opening (mm)	Sieve Opening (in.)	Type A Spec. Requirements (% passing)	Type B Spec. Requirements (% passing)
450	18	1	1
300	12	100 %	100 %
200	8	100 %	75–100 %
100	4	100 %	...
75	3	95–100 %	0–85 %
38	1.5	0–70 %	0–25 %
4.75	0.187 (No. 4)	0–5 %	0–1 %
pan	pan	0 %	0 %
Free steel		1 % max	1 % max
Longest shred (in.)		10	18
% weight of shred >12 in. long		...	16 % max
Sidewall shreds (ea)		0	0
Shreds >2 in. wire exposed		10 % max	10 % max
Shreds >1 in. wire exposed		25 % max	25 % max

severed from the side wall. A minimum of 75 % (by weight) shall pass the 200-mm square mesh sieve, a maximum of 85 % (by weight) shall pass the 75-mm square mesh sieve, a maximum of 25 % (by weight) shall pass the 38-mm square mesh sieve, and a maximum of 1 % (by weight) shall pass the 4.75-mm sieve, as summarized in Table 2.

8. Leachate

8.1 The Toxicity Characteristics Leaching Procedure (TCLP) (USEPA Method 1311) is one test to determine if a waste is regulated as a hazardous waste due to leaching of toxic compounds that could pose a significant hazard to human health. The TCLP test represents the scenario of acid rain percolating through the waste and exiting as leachate. For all regulated metals and organics, the results for TDA are well below the TCLP regulatory limits (28-30); therefore, TDA are not classified as a hazardous waste.

8.2 In addition to TCLP tests, laboratory leaching studies have been performed following several test protocols. Results show that metals are leached most readily at low pH and that organics are leached most readily at high pH (30, 31). Thus, it is preferable to use TDA in environments with a near neutral pH.

8.3 The potential of TDA to generate leachate has been examined in field studies for both above- and below-groundwater table applications. The results have been compared to primary drinking water standards, secondary (aesthetic) drinking water standards, and USEPA preliminary remediation goals (PRG) (32). PRG are risk-based concentrations that the USEPA considers to be protective for lifetime exposure to humans (32). Freshwater aquatic toxicity has also been evaluated. These results were summarized in a literature review and statistical analysis performed for the USEPA Resource Conservation Challenge (33).

8.4 In above-groundwater table applications, the TDA is placed above the water table and is subjected to water from infiltration. Seven field studies have examined this category of applications (34-41). A statistical comparison was performed (33) using procedures for censored environmental data recommended by Helsel (42).

8.4.1 The preponderance of evidence shows that TDA used above the water table does not cause the primary drinking water standards for metals to be exceeded. Moreover, a statistical comparison shows that TDA is unlikely to increase levels of metals with primary drinking water standards above naturally occurring background levels (33).

8.4.2 For above-groundwater table applications, it is likely that TDA would increase the concentrations of iron and manganese, which have secondary drinking water standards. At the point where water emerges from a TDA fill, it is likely that the levels of iron and manganese will exceed secondary drinking water standards, and the PRG for tap water for manganese will also be exceeded. After an extended dry period, an initial pulse of iron and manganese mass may occur (43). When a TDA septic tank leach field serviced with typical domestic wastewater sewage was compared with a leach field comprised of rock aggregate media, iron, manganese, and zinc concentrations from the TDA effluent were statistically significantly higher compared to the rock media, which is likely a result of oxidation of metallic components in the TDA (26). However, for two of three projects where samples were taken from wells adjacent to the TDA fills, the iron and manganese levels were about the same as background levels. The prevalence of manganese in groundwater is shown by the naturally occurring concentrations at three projects being above the secondary drinking water standard and PRG. For other chemicals with secondary drinking water standards, a statistical comparison shows that there is no evidence that TDA affects naturally occurring background levels (33).

8.4.3 Volatile and semivolatile organics have been monitored on two projects where TDA was placed above the water table (35-37). Substances are generally below detection limits. Moreover, for those substances with drinking water standards, the levels were below the standards. The concentrations were also below the applicable PRG (33). A few substances were occasionally found above the test method detection limit; however, the highest concentrations were found in a control section located uphill from the TDA (35), suggesting a source associated with active roadways. There are also laboratory studies showing that TDA has the ability to absorb some organic compounds (44).

8.4.4 Aquatic toxicity tests were performed on samples taken from one above-groundwater table project. The results showed that water collected directly from TDA fills had no effect on survival, growth, and reproduction of two standard test species (fathead minnows and a small crustacean (*Ceriodaphnia dubia*)) (33, 36).

8.4.5 In summary, TDA placed above the water table would be expected to have a negligible off-site effect on water quality (33).

8.5 TDA placed below the water table has been studied at three different sites (45). A statistical comparison was performed (33) using procedures for censored environmental data recommended by Helsel (42).

8.5.1 A statistical analysis of the data at these sites showed that use of TDA did not cause primary drinking water standards for metals to be exceeded. Moreover, the data shows that TDA

was unlikely to increase levels of metals with primary drinking water standards above naturally occurring background levels (33).

8.5.2 For chemicals with secondary drinking water standards, it is likely that TDA below the groundwater table would increase the concentrations of iron, manganese, and zinc. For water that is collected directly from TDA fill below the groundwater table, it is likely that the concentrations of manganese and iron will exceed their secondary drinking water standards and PRG for tap water. The secondary drinking water standards and PRG for zinc were not exceeded even for water in direct contact with TDA. The rate at which metals leach from TDA is the highest when constantly submerged, but release rates decrease over time, where it significantly decreases after eight months and becomes constant by the end of 15 months at very low values; iron and manganese will likely be released from a submerged TDA fill at low, detectable rates for the lifetime of typical civil engineering applications (43). The concentration of iron, manganese, and zinc decreases to near background levels by flowing only a short distance through soil (0.6 to 3.3 m). For other chemicals with secondary drinking water standards, a statistical comparison showed little likelihood that TDA placed below the water table alters naturally occurring background levels (33).

8.5.3 Trace levels of a few volatile and semivolatile organics were found from water taken directly from TDA-filled trenches. The concentration of benzene, chloroethane, cis-1,2-dichloroethene, and aniline for water in direct contact with TDA are above their respective PRG for tap water. However, chloroethane, cis-1,2-dichloroethene, and aniline concentrations were below the PRG for all samples taken from wells 0.6 and 3.3 m downgradient. Moreover, the concentrations were below the detection limits for virtually all samples, indicating that these substances have limited downgradient mobility (30).

8.5.4 The data on benzene deserves additional discussion. The primary drinking water standard for benzene is 5 µg/L and its PRG is 0.35 µg/L. For six sample dates, the detection limit reported by the laboratory was 0.5 µg/L, slightly above the PRG. For the remaining four sample dates the detection limit was 5 µg/L. Focusing on the data from samples with a detection limit of 0.5 µg/L, the benzene concentration was below the detection limit in downgradient wells for all but one well, on a single date, when the concentration was 1 µg/L. This data shows that benzene also has limited downgradient mobility (30). In a different study where TDA was submerged in water for 15 months, the highest benzene concentration of 0.97 µg/L was observed at the beginning of the experiment, but dropped below detection limit of 0.3 µg/L by Week 34 (43). This study indicated that the specific loss rates for benzene are highest at the beginning, and decline rapidly over the first 18 weeks (43).

8.5.5 Aquatic toxicity tests were performed on samples taken on two dates. The results showed that water collected directly from TDA-filled trenches had no effect on survival and growth of fathead minnows. While there were some toxic effects of TDA placed below the groundwater table on *Ceriodaphnia dubia*, a small amount of dilution (up to threefold) as

the groundwater flowed downgradient or when it entered a surface body of water would remove the toxic effects (33, 36).

8.5.6 In summary, TDA placed below the water table would be expected to have a negligible off-site effect on water quality (33).

9. Keywords

9.1 construction practices; landfills; leachate; lightweight fill; rail lines; retaining walls; roads; scrap tires; TDA; tire chips; tire-derived aggregate; tire shreds; vibration damping

APPENDIX

(Nonmandatory Information)

X1. TYPICAL MATERIAL PROPERTIES

X1.1 This appendix contains typical properties of TDA to aid in the selection of values for preliminary designs and to provide a basis for comparison for test results.

X1.2 Values of specific gravity and water absorption capacity reported in the literature are summarized in Table X1.1. The unit weight of TDA changes with placement and compaction conditions and the application of overburden stress, as summarized in Table X1.2 (8). Table X1.3 summarizes the compacted and uncompacted dry density of TDA. Compaction results for mixtures of TDA and soil also are available (4-6, 46). The results from one study are summarized in Fig. X1.1.

X1.3 Typical compressibility results are summarized in Table X1.4. The compressive properties between the different types of TDA are equivalent after initial compaction or compression (26). Increased compressive loading results in a reduction in hydraulic conductivity.

X1.4 A measure of compressibility applicable to vehicle loads is resilient modulus. Results determined by Ahmed (5) using AASHTO T 274-82 for mixtures of TDA and soil are summarized in Table X1.5. The parameter A , and therefore M_R , decreases as the percent TDA by dry weight of the mix increases. Results determined by Edil and Bosscher (4, 51) for mixtures of TDA and sand are summarized in Fig. X1.2. Shao et al. (53) performed resilient modulus tests on crumb rubber (7 mm maximum size) and rubber buffings (1 mm maximum size). The resilient modulus values ranged from 700 to 1700 kPa.

X1.5 Typical values of coefficient of lateral earth pressure at rest and Poisson's ratio, measured as part of vertical compression tests, are presented in Table X1.6.

X1.6 The shear strength of TDA has been measured using triaxial shear (5, 48, 53), simple shear (13), interface direct shear (13), and using direct shear (12, 13, 46, 49, 54). Tables X1.7-X1.12 summarize the Type B TDA shear test results of: simple shear testing of Type B TDA; internal interface direct shear testing of Type B TDA (DS); TDA and concrete interface direct shear testing of Type B TDA (DSI); TDA and sand interface direct shear testing of Type B TDA (DSIS); TDA and aggregate interface direct shear testing of Type B TDA (DSIA); and TDA and clay interface direct shear testing of Type B TDA (DSIC), respectively, from McCartney et al. (13, 55). Available shear strength data give cohesion $c = 13$ to 14 kPa (8). Failure

envelopes for tests conducted at low stress levels (less than about 100 kPa) are compared in Figs. X1.3 and X1.4. The internal shear strength failure envelopes are nonlinear and concave down, with a secant friction angle varying from approximately 30 to 39° (13), so when fitting a linear failure envelope to the data, it is important that this be done over the range of stresses that will occur in the field. The TDA-concrete interface failure envelope is linear, with a friction angle of approximately 22.6° (13). Tables X1.13 and X1.14 summarize the geogrid pullout (PO) test results and the TDA interface shear strength test results, respectively, from McCartney et al. (55). Each test was conducted to a minimum displacement of 12 in. (300 mm) or until both peak and large displacement shear strengths values were obtained.

X1.7 The shear strength of TDA/soil mixtures has been measured using triaxial shear (5, 56) and direct shear (4, 57). Tables X1.15 and X1.16 summarize the results from Ahmed (5). Edil and Bosscher (4), and Benson and Khire (57) were primarily interested in the reinforcing effect of TDA when added to a sand. Under some circumstances, the shear strength is increased by adding TDA.

X1.8 Typical hydraulic conductivities for TDA and mixtures of TDA and soil are reported in Tables X1.17 and X1.18, and Fig. X1.5.

X1.9 Measured thermal conductivities ranged from 0.0838 Cal/m-hr-°C for 1-mm particles tested in a thawed state with a water content less than 1 % and with low compaction to 0.147 Cal/m-hr-°C for 25-mm TDA tested in a frozen state with a water content of 5 % and high compaction (53). The thermal conductivity increased with increasing particle size, increased water content, and increased compaction. The thermal conductivity was higher for TDA tested under frozen conditions than when tested under thawed conditions. A thermal conductivity of 0.2 Cal/m-hr-°C was back-calculated from a field trial constructed using TDA with a maximum size of 51 mm (59). It is reasonable that the back-calculated thermal conductivity is higher than found by Shao et al. (53) since the TDA for the former were larger and contained more steel bead wire and steel belt.

X1.10 The results of TCLP tests for regulated metals are summarized in Table X1.19. Results of field studies of the effect of TDA on water quality are summarized in Tables X1.20 and X1.21, as well as Figs. X1.6 and X1.7.

X1.11 Time-dependent settlement for a Type B, 15-ft TDA fill between one and seven years can be estimated using a logarithmic curve, shown in Fig. X1.8. The settlement rate

begins to decrease after three years (1095 days), at approximately 2 % strain, which corresponds to approximately 9.4 cm of settlement for a 4.6-m TDA fill (63).

TABLE X1.1 Summary of Specific Gravity and Water Absorption Capacity

TDA Type	Specific Gravity			Water Absorption Capacity (%)	Reference
	Bulk	Saturate Surface Dry	Apparent		
Steel belted Mixture	1.06	1.01	1.10	4	(47)
Mixture (Pine State)	1.06	1.16	1.18	9.5	(48)
Mixture (Palmer)	----	----	1.24	2	(46)
Mixture (Sawyer)	----	----	1.27	2	(46)
Mixture	1.01	1.05	1.23	4.3	(47)
Mixture (12.7 mm to 50.8 mm)	----	0.88 to 1.13	----	----	(5)

TABLE X1.2 Unit Weight of Large-Size TDA

TDA size (mm)	Uncompacted Unit Weight (kN/m ³)	Compacted Unit Weight (kN/m ³)	Compaction Effort	Specimen Size ^A (mm)	Reference
≤76	3.35	6.07	60 % of standard Proctor energy	254(D) × 254(H)	(49)
50–305	N/A ^B	4.71–6.30	Laboratory compaction	Varies	(50)
≤178	N/A ^B	4.47	N/A ^B	305 (L) × 305 (W)	(9)
≤76	3.30–4.88	5.03–6.92	Laboratory compaction	Varies	(13)
		6.45–7.54	Field compaction		(13)
38–125	4.90 ^C	6.31	Cyclic loading with a maximum of 54 kPa	570 (D) × 1120 (H)	(13)
		6.48	Cyclic loading with a maximum of 134 kPa		
35–125 (OTR) ^D	4.80 ^C	6.11	Cyclic loading with a maximum of 58 kPa		
		6.24	Cyclic loading with a maximum of 146 kPa		

^A D, L, W, and H = diameter, length, width, and height, respectively.

^B Not available.

^C Under a vertical stress of 50 to 60 kPa.

^D Off-the-road TDA.

TABLE X1.3 Summary of Laboratory Dry Densities of TDA

Compaction Method ^A	Particle Size Range (mm)	TDA Type	Source of TDA	Dry Density (kg/m ³)	Reference
Loose	2 to 75	Mixed	Palmer Shredding	341	(46, 49)
Loose	2 to 51	Mixed	Pine State Recycling	482	(46, 49)
Loose	2 to 25	Glass	F&B Enterprises	495	(46, 49)
Loose	2 to 51	Mixed	Sawyer Environmental	409	(3, 47)
Loose	51 max	Mixed	----	466	(5, 6)
Loose	25 max	Mixed	----	489	(5, 6)
Vibration	25 max	Mixed	----	496	(5, 6)
Vibration	13 max	Mixed	----	473	(5, 6)
50 % Standard	51 max	Mixed	----	614	(5, 6)
50 % Standard	25 max	Mixed	----	641	(5, 6)
60 % Standard	2 to 75	Mixed	Palmer Shredding	620	(46, 49)
60 % Standard	2 to 51	Mixed	Pine State Recycling	643	(46, 49)
60 % Standard	2 to 25	Glass	F&B Enterprises	618	(46, 49)
60 % Standard	2 to 51	Mixed	Sawyer Environmental	625	(3, 47)
Standard	2 to 51	Mixed	Sawyer Environmental	640	(3, 47)
Standard	51 max	Mixed	----	635	(5, 6)
Standard	38 max	Mixed	----	645	(5, 6)
Standard	25 max	Mixed	----	653	(5, 6)
Standard	13 max	Mixed	----	633	(5, 6)
Standard	20 to 75	----	Rodefled	594 ^B	(4, 51)
Standard	20 to 75	----	Rodefled	560 ^C	(4, 51)
Modified	2 to 51	Mixed	Sawyer Environmental	660	(3, 47)
Modified	51 max	Mixed	----	668	(5, 6)
Modified	25 max	Mixed	----	685	(5, 6)
----	50.8	Mixed	----	410 to 570	(48)

^A Compaction methods:

Loose = no compaction; TDA loosely dumped into compaction mold.

Vibration = Test Methods D4253.

50 % Standard = Impact compaction with compaction energy of 296.4 kJ/m³.

60 % Standard = Impact compaction with compaction energy of 355.6 kJ/m³.

Standard = Impact compaction with compaction energy of 296.4 kJ/m³.

Modified = Impact compaction with compaction energy of 2693 kJ/m³.

^B 152-mm diameter mold compacted by 4.54 kg rammer falling 305 mm.

^C 305-mm diameter mold compacted by 27.4 kg rammer falling 457 mm.

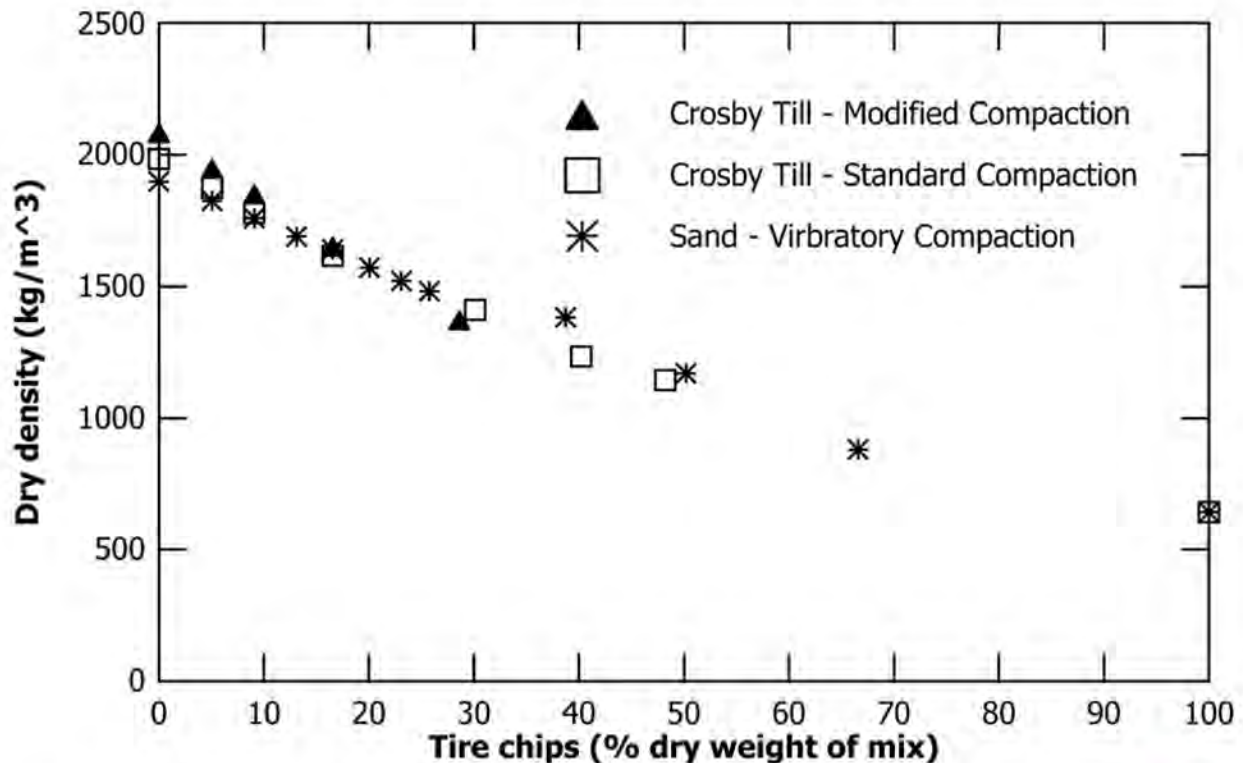


FIG. X1.1 Comparison of Compacted Dry Density of Mixtures of TDA with Ottawa Sand and Crosby Till (5)

TABLE X1.4 Compressibility on Initial Loading

Particle Size Range (mm)	TDA Type	TDA Source	Initial Dry Density (kg/m ³)	Vertical Strain (%) at Indicated Vertical Stress (kPa)					Reference
				10	25	50	100	200	
2 to 75	Mixed	Palmer	Compacted	7 to 11	16 to 21	23 to 27	30 to 34	38 to 41	(47)
2 to 51	Mixed	Pine State	Compacted	8 to 14	15 to 20	21 to 26	27 to 32	33 to 37	(46)
2 to 25	Glass	F&B	Compacted	5 to 10	11 to 16	18 to 22	26 to 28	33 to 35	(46)
2 to 51	Mixed	Sawyer	Compacted	5 to 10	13 to 18	17 to 23	22 to 30	29 to 37	(47)
	Mixed		Compacted	4 to 5	8 to 11	13 to 16	18 to 23	27	(5)
75 max	Mixed	Pine State	510 to 670	12 to 20	18 to 28	----	----	----	(10)
2 to 51	Mixed	Pine State	Loose	18	34	41	46	52	(46)
2 to 25	Mixed	F&B	Loose	8	18	28	37	45	(46)
	----		Loose	9	12 to 17	17 to 24	24 to 31	30 to 38	(52)

TABLE X1.5 Resilient Modulus of TDA and TDA/Soil Mixtures (5)

NOTE 1—Constants A and B are the constants for the regression equation and r^2 is the regression coefficient.

NOTE 2—Standard = Standard Proctor Energy = 296.4 kJ/m³.

NOTE 3—The constants A and B assume the units for θ and M_R are psi (1 psi = 6.89 kPa).

Test No.	TDA Max Size (mm)	Sample Preparation	% TDA Based on Total Weight	Soil Type	Constant A	Constant B	r^2
AH01	No shreds	Vibratory	No shreds	Sand	1071.5	0.84	0.95
AH02	13	Vibratory	15	Sand	524.8	0.83	0.95
AH03	13	Vibratory	30	Sand	269.2	0.90	0.67
AH04	13	Vibratory	38	Sand	42.7	1.15	0.89
AH05	13	Vibratory	50	Sand	38.9	0.83	0.84
AH06	13	Vibratory	100	Sand	36.3	0.55	0.74
AH07	19	Vibratory	38	Sand	34.7	1.21	0.92
AH08	No shreds	Standard	No shreds	Crosby Till	3162.3	0.49	0.83
AH09	13	Standard	15	Crosby Till	53.7	1.15	0.91
AH10	13	Standard	29	Crosby Till	61.7	0.91	0.94
AH11	13	Standard	38	Crosby Till	55.0	0.67	0.95

TABLE X1.6 Summary of Coefficient of Lateral Earth Pressure at Rest and Poisson's Ratio

Particle Size Range (mm)	TDA Type	Source of TDA	K_D	$-\mu$	Reference
2 to 51	Mixed	Sawyer Environmental	0.44	0.30	(3, 47)
2 to 75	Mixed	Palmer Shredding	0.26	0.20	(46, 49)
2 to 51	Mixed	Pine State Recycling	0.41	0.28	(46, 49)
2 to 25	Glass	F&B Enterprises	0.47	0.32	(46, 49)
----	----	----	----	0.3 to 0.17	(4, 51)
13 to 51	Mixed	Maust Tire Recyclers	0.4 ^A	0.3	(52)

^A For vertical stress less than 172 kPa.

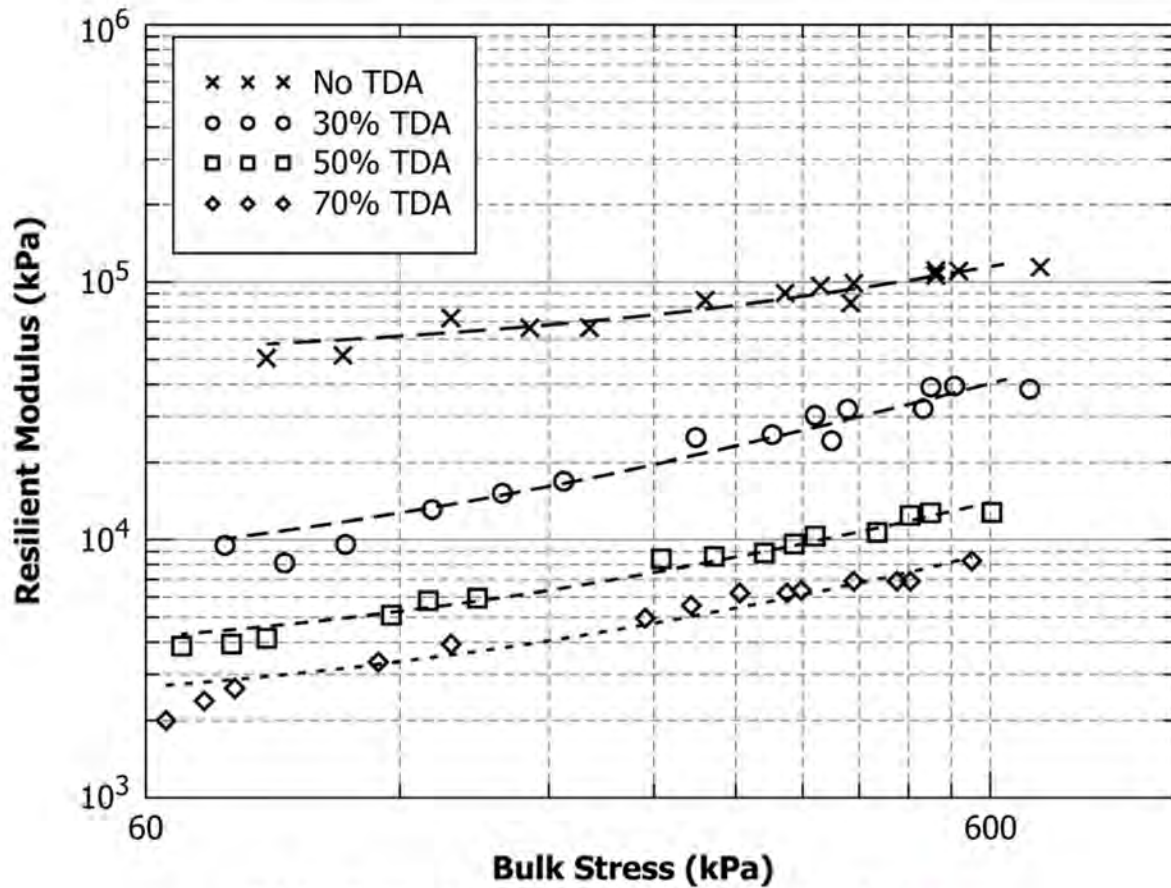


FIG. X1.2 Resilient Modulus of Mixtures of TDA and Clean Sand (4)

TABLE X1.7 Simple Shear Testing of Type B TDA (13)

Shear Strain Amplitude (%)	Max. Shear Force (kN)	Min. Shear Force (kN)	Max. Disp. (mm)	Min. Disp. (mm)	Max Shear Strain (%)	Min Shear Strain (%)	Shear Modulus (kPa)	Shear Stiffness (kN/m)	A _L (kN-mm)	A _T (kN-mm)	D (%)
0.1	5.0	-8.0	1.4	-1.7	0.1	-0.11	1779	4141	15	5	23.6
0.3	10.2	-13.7	6.6	-3.0	0.4	-0.19	1068	2487	65	29	17.9
1	21.1	-24.6	16.8	-14.8	1.1	-0.93	619	1441	393	181	17.3
3	39.4	-41.2	47.9	-47.0	3.0	-2.93	365	850	2270	956	18.9
0.3	13.5	-8.4	4.4	-5.2	0.3	-0.32	983	2289	63	26	19.3
0.1	8.2	-3.8	1.4	-1.7	0.1	-0.11	1622	3776	16	5	26.6
3	38.3	-42.4	45.6	-49.4	2.9	-3.09	365	850	2325	960	19.3
10	77.1	-69.5	153.0	-161	9.6	-10.1	200	466	16 303	5760	22.5
0.1	10.4	-6.8	1.6	-1.6	-0.1	0.1	2282	5313	18	7	21.0
0.3	17.2	-14.4	5	-5.0	0	0.3	1417	3299	84	38	17.8
1.0	36.6	-30.7	16	-16.1	-1	1.0	877	2041	518	260	15.8
3.0	64.8	-60.3	47	-48.4	-3	3.0	561	1307	3253	1498	17.3
10	125	-126	161	-158	-10	10	338	787	24 382	10 009	19.4
0.1	9.1	-13.1	1.5	-1.6	0.1	-0.1	3097	7210	25	9	23.4
0.3	17.9	-23.3	4.7	-4.9	0.3	-0.3	1854	4317	118	49	19.2
1	41.9	-45.2	15.7	-16.1	1.0	-1.0	1177	2741	749	346	17.2
3	81.6	-84.5	47.3	-48.5	3.0	-3.0	745	1734	4528	1990	18.1
10	167	-174	157	-163	10	-10	458	1066	31 900	13 646	18.6
0.1	16.1	-11.0	1.8	-1.7	-0.1	0.1	3355	7810	32	112	21.4
0.3	27.8	-22.2	5.2	-5.0	-0.3	0.3	2087	4860	153	64	19.0
1	53.0	-45.3	17.2	-17.6	-1.1	1.1	1212	2822	961	427	17.9
3	100.4	-92.8	53.3	-54.6	-3.4	3.3	770	1791	5760	2604	17.6
10	192	-197	161	-158	-10	10.1	524	1220	35 174	15 515	18.0

TABLE X1.8 Direct Shear Testing of Type B TDA (13)

Test #	Initial TDA Unit Weight (kN/m ³)	Initial Void Ratio	Displacement Rate (mm/min)	Initial Normal Stress, σ_0 (kPa)	Values at Peak Shear Strength			Average Dilatation Angle, Ψ (deg)
					σ (kPa)	τ (kPa)	φ_{sec} (deg)	
DS 1	6.45	0.75	1	23.8	27.3	23.6	41.1	3.6
DS 2	6.60	0.71	10	24.4	27.5	23.1	40.1	4.7
DS 3	6.56	0.72	100	24.3	27.3	22.9	40.0	3.7
DS 4	5.60	1.01	10	23.8	33.1	26.6	38.8	2.9
DS 5	5.04	1.24	10	19.5	27.0	21.7	38.8	3.1
DS 6	6.35	0.78	10	38.8	57.7	40.6	35.1	2.6
DS 7	7.58	0.49	10	60.8	71.0	46.6	33.3	1.3
DS 8	8.04	0.40	10	76.7	88.4	51.5	30.2	1.2

TABLE X1.9 Interface Direct Shear Testing of Type B TDA (13)

Test #	Initial TDA Unit Weight (kN/m ³)	Initial Void Ratio	Displacement Rate (mm/min)	Initial Normal Stress, σ_0 (kPa)	Values at Peak Shear Strength		
					σ (kPa)	τ (kPa)	φ_{sec} (deg)
DSI 1	7.26	0.55	10	22.3	29.9	12.1	22.0
DSI 2	7.12	0.58	10	39.5	52.8	20.4	21.1
DSI 3	7.40	0.52	10	55.4	65.1	26.2	21.9
DSI 4	7.38	0.53	10	77.0	100.7	39.7	21.5

TABLE X1.10 TDA-Sand Interface Direct Shear Testing of Type B TDA (55)

Test #	Initial TDA Unit Weight (kN/m ³)	Initial Void Ratio	Displacement Rate (mm/min)	Initial Normal Stress, σ_0 (kPa)	Values At Peak Secant Friction Angle			
					σ (kPa)	τ (kPa)	φ_{sec} (deg)	δ_t (mm)
DSIS 1	7.2	0.57	10	38.8	43.3	27.1	32.0	323.5
DSIS 2	7.4	0.51	10	58.7	66.2	43.4	31.3	349.6
DSIS 3	8.0	0.41	10	76.7	76.7	51.7	30.9	345.0

TABLE X1.11 TDA-Aggregate Interface Direct Shear Testing of Type B TDA (55)

Test #	Initial TDA Unit Weight (kN/m ³)	Initial Void Ratio	Displacement Rate (mm/min)	Initial Normal Stress, σ_0 (kPa)	Values At Peak Secant Friction Angle			
					σ (kPa)	τ (kPa)	φ_{sec} (deg)	δ_t (mm)
DSIA 1	6.46	0.75	10	19	20.8	13.5	33	259.9
DSIA 2	6.98	0.71	10	24	26.8	16.3	31.2	326.8
DSIA 3	7.01	0.61	10	33.7	35.4	17.8	26.7	145.3
DSIA 4	7.35	0.53	10	49.3	53.2	27.5	27.3	229.7
DSIA 5	6.61	0.71	10	24	26.1	16.2	31.9	260.1

TABLE X1.12 TDA-Clay Interface Direct Shear Testing of Type B TDA (55)

Test #	Initial TDA Unit Weight (kN/m ³)	Initial Void Ratio	Displacement Rate (mm/min)	Initial Normal Stress, σ_0 (kPa)	Values At Peak Secant Friction Angle			
					σ (kPa)	τ (kPa)	φ_{sec} (deg)	δ_t (mm)
DSIC 1	6.97	0.62	10	38.3	41.9	25.5	31.4	263.1
DSIC 2	7.5	0.5	10	58.9	64.2	36.9	29.9	250.7
DSIC 3	8.0	0.41	10	76.7	86.1	48.1	29.2	335.4

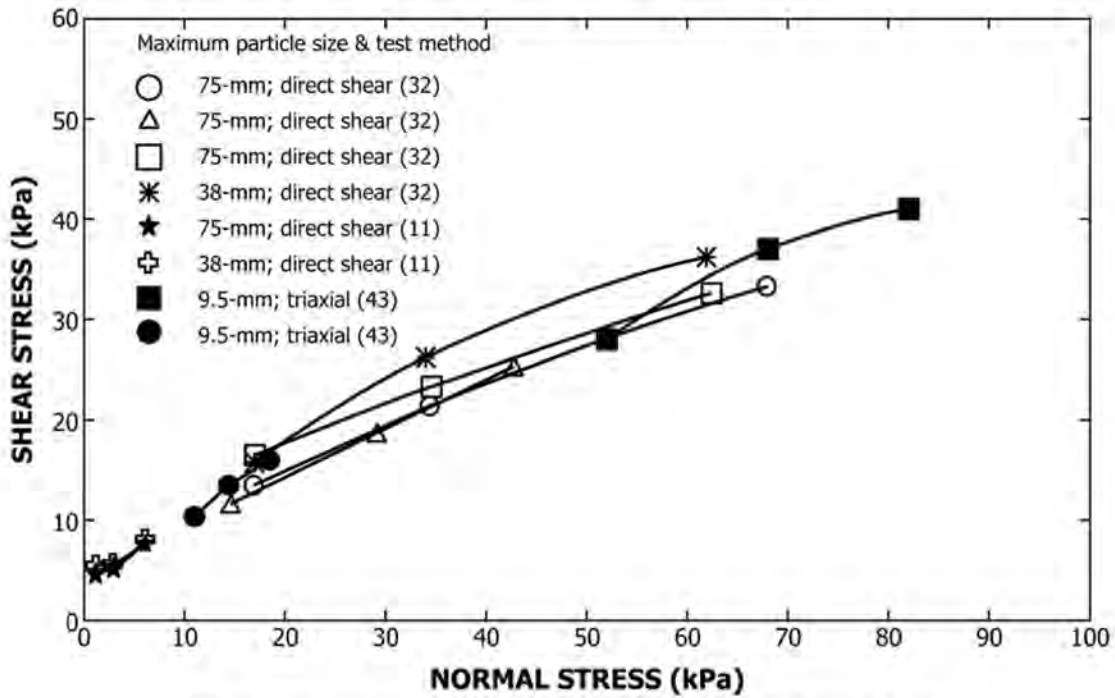


FIG. X1.3 Comparison of Failure Envelopes of TDA at Low Stress Levels

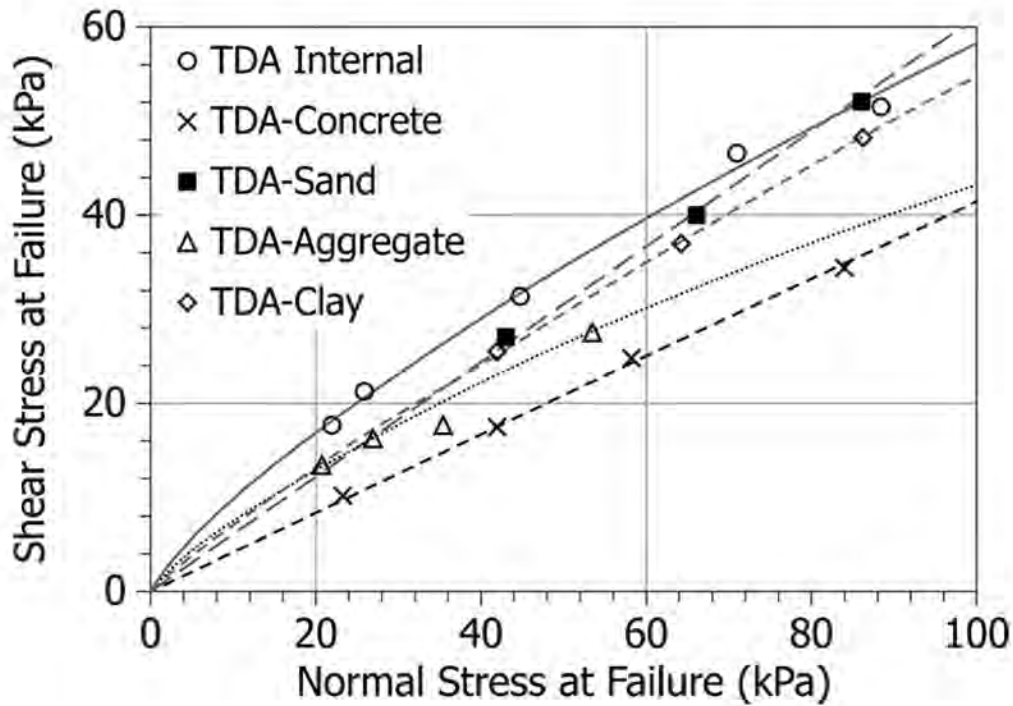


FIG. X1.4 Comparison of Failure Envelopes of TDA for All Interfaces at Low Stress Levels

TABLE X1.13 Pullout Testing Programs of Type B TDA (55)

NOTE 1—Test was conducted to a minimum displacement of 1 ft (300 mm).

Test No.	Test Reference	Initial Normal Stress		Geogrid Type
		(psf)	(kPa)	
1	PO1 UX	210	10.1	Tensar UX1100
2	PO2 UX	400	19.2	Tensar UX1100
3	PO3 UX	804	38.5	Tensar UX1100
4	PO4 UX	1213	58.1	Tensar UX1100
5	PO1 5XT	401	19.2	Miragrid 5XT
6	PO2 5XT	614	29.4	Miragrid 5XT
7	PO3 5XT	805	38.6	Miragrid 5XT
8	PO4 5XT	1000	47.9	Miragrid 5XT
9	PO5 5XT	1212	58.1	Miragrid 5XT
10	PO1 BX	210	9.5	Tensar BX1500
11	PO2 BX	404	19.4	Tensar BX1500
12	PO3 BX	610	29.3	Tensar BX1500

TABLE X1.14 Interface Shear Testing of Type B TDA (55)

NOTE 1—Test was conducted until both peak and large displacement shear strengths values were obtained.

Test No.	Test Reference	Initial Normal Stress		Soil	Geotextile
		(psf)	(kPa)		
1	DSIS 1	810	38.8	Sand	Mirafi 140N
2	DSIS 2	1225	58.7	Sand	Mirafi 140N
3	DSIS 3	1601	76.7	Sand	Mirafi 140N
4	DSIA 1	397	19	Aggregate	Mirafi 600x
5	DSIA 2	500	24	Aggregate	Mirafi 600x
6	DSIA 3	704	33.7	Aggregate	Mirafi 600x
7	DSIA 4	1028	49.3	Aggregate	Mirafi 600x
8	DSIA 5	500	24	Aggregate	Mirafi 140N
9	DSIC 1	799	38.3	Clay	Mirafi 140N
10	DSIC 2	1230	58.9	Clay	Mirafi 140N
11	DSIC 3	1601	76.7	Clay	Mirafi 140N

TABLE X1.15 Shear Strength of Mixtures of TDA and Ottawa Sand (5)

NOTE 1—All samples are prepared by using vibratory compaction.

NOTE 2—Chip ratio is the air-dried weight to chips divided by dry weight of mix, expressed in percent.

NOTE 3— $\sin \phi = \tan \alpha$; $c = a/\cos \phi$.

Test No.	Size of Chips (in.)	Chip/Mix Ratio (%)	Confining Pressure (psi)	Strain Levels (%)	a (psi)	$\tan \alpha$	r^2	c (psi)	ϕ (°)
TRS01	No-Chip	0	4.50	5	-0.24	0.6615	0.9998	0	41.41
TRS02	No-Chip	0	14.36	10	-	-	-	-	-
TRS03	No-Chip	0	28.86	15	-	-	-	-	-
TRS04	1.00	16.5	4.64	5	2.17	0.6006	0.9996	2.71	36.91
TRS05	1.00	16.5	14.50	10	1.05	0.6252	0.9998	1.35	38.70
TRS06	1.00	16.5	28.86	15	-	-	-	-	-
TRS07	1.00	29.16	4.50	5	5.52	0.4944	0.9943	6.35	29.63
TRS08	1.00	29.16	14.50	10	3.04	0.6110	0.9992	3.84	37.66
TRS09	1.00	29.16	28.86	15	2.65	0.6286	0.9993	3.41	38.95
TRS10	1.00	40.00	4.64	5	5.15	0.3957	0.9988	5.61	23.31
TRS11	1.00	40.00	14.36	10	5.13	0.5413	0.9972	6.10	32.77
TRS12	1.00	40.00	28.86	15	4.09	0.6013	0.9999	5.12	36.96
TRS13	1.00	50.00	4.64	5	-0.68	0.3562	0.9601	0.00	20.87
TRS14	1.00	50.00	14.36	10	4.54	0.4362	0.9988	5.05	25.86
TRS15	1.00	50.00	28.71	15	3.84	0.5519	0.9986	4.60	33.50
TRS16	1.00	66.54	4.50	5	2.23	0.1699	0.9999	2.26	9.78
TRS17	1.00	66.54	14.36	10	1.89	0.3324	0.9901	2.00	19.41
TRS18	1.00	66.54	28.71	15	4.91	0.3759	0.9992	5.30	22.08
TRS19	0.50	37.85	4.64	5	5.26	0.3891	0.9998	5.71	22.90
TRS20	0.50	37.85	14.50	10	5.48	0.5383	1.0000	6.50	32.57
TRS21	0.50	37.85	28.71	15	4.42	0.6238	0.9998	5.66	38.59
TRS22	1.00	38.78	4.64	5	6.55	0.4299	0.9964	7.25	25.46
TRS23	1.00	39.32	14.36	10	5.17	0.5684	0.9985	6.28	34.64
TRS24	1.00	39.37	28.71	15	4.08	0.617	0.9999	5.18	38.10

TABLE X1.16 Shear Strength of Mixtures of TDA and Crosby Till (5)

NOTE 1—Chip ratio is the air-dried weight of chips divided by dry weight of mix, expressed in percent.

 NOTE 2— $\sin \phi = \tan \alpha$; $c = a/\cos \phi$.

Test No.	Size of Chips (in.)	Chip Ratio (%)	Confining Pressure (psi)	Strain Levels (%)	a (psi)	$\tan \alpha$	r^2	c (psi)	ϕ (°)
TRC01	No-Chip	0	4.50	5	6.14	0.4299	0.9970	6.80	25.46
TRC02	No-Chip	0	14.50	10	9.28	0.4914	1.0000	10.66	29.43
TRC03	No-Chip	0	28.71	15	9.72	0.5099	0.9996	11.30	30.66
				20	9.58	0.5151	0.9996	11.18	30.00
TRC04	1.00	16.27	4.64	5	7.43	0.3873	0.9979	8.06	22.79
TRC05	1.00	16.27	14.36	10	6.21	0.5810	0.9982	7.63	35.52
TRC06	1.00	16.27	28.71	15	7.77	0.5686	0.9992	9.45	34.65
				20	5.71	0.6232	0.9992	7.30	38.55
TRC07	1.00	30.18	44.52	5	6.82	0.2612	0.9991	7.67	15.14
TRC08	1.00	30.18	14.36	10	9.96	0.3740	0.9997	10.74	21.96
TRC09	1.00	30.18	28.86	15	9.88	0.4748	0.9973	11.23	28.35
				20	8.82	0.5460	0.9971	10.53	33.09
TRC10	1.00	40.05	4.64	5	5.50	0.2205	0.9947	5.64	12.74
TRC11	1.00	40.05	14.36	10	7.65	0.3598	0.9990	8.20	21.09
TRC12	1.00	40.05	28.71	15	8.19	0.4543	0.9991	9.42	27.02
				20	8.44	0.5271	0.9999	9.93	31.81
TRC13	1.00	48.49	4.64	5	4.93	0.2025	0.9985	5.03	11.68
TRC14	1.00	48.49	14.36	10	6.69	0.3472	0.9999	7.13	20.32
TRC15	1.00	48.49	28.86	15	7.81	0.4441	0.9999	8.72	26.37
				20	7.92	0.5208	0.9999	9.28	31.39
TRC16	0.50	39.80	4.64	5	6.17	0.1173	0.9980	6.21	6.74
TRC17	0.50	39.80	14.36	10	9.37	0.2181	0.9875	9.60	12.60
TRC18	0.50	39.80	28.86	15	11.07	0.3130	0.9866	11.66	18.24
TRC19	0.50	39.64	14.36						
TRC20	0.50	39.79	14.36						

TABLE X1.17 Summary of Reported Hydraulic Conductivities of TDA

Particle Size (mm)	Void Ratio	Dry Density (kg/m ³)	Hydraulic Conductivity (cm/s)	Reference
25 to 64		469	5.3 to 23.5	(48)
25 to 64		608	2.9 to 10.9	
5 to 51		470	4.9 to 59.3	
5 to 51		610	3.8 to 22.0	
38	-----	-----	1.4 to 2.6	(58)
19	-----	-----	0.8 to 2.6	
10 to 51	0.925	644	7.7	(46, 49)
10 to 51	0.488	833	2.1	
20 to 76	1.114	601	15.4	
20 to 76	0.583	803	4.8	
10 to 38	0.833	622	6.9	
10 to 38	0.414	808	1.5	
10 to 38		653	0.58	(5)

TABLE X1.18 Hydraulic Conductivities of Mixtures of TDA and Soil (5)

TDA Max Size (mm)	Soil Type	% TDA Based on Total Weight	Dry Density (kg/m ³)	Hydraulic Conductivity (cm/s)
-----	Ottawa Sand	0	1890	1.6×10^{-4}
25	Ottawa Sand	15.5	1680	1.8×10^{-3}
25	Ottawa Sand	30.1	1530	3.5×10^{-3}
25	Ottawa Sand	37.7	1410	8.7×10^{-3}
-----	Crosby till	0	1910	8.9×10^{-7}
25	Crosby till	14.8	1700	1.8×10^{-6}
25	Crosby till	30.1	1390	2.1×10^{-3}
25	Crosby till	40	1200	8.8×10^{-3}
13	Crosby till	40	1190	9.7×10^{-3}

TABLE X1.19 Summary of TCLP Results for Regulated Metals (28-30)

Concentration in Extract	Ag µg/L (ppb)	As µg/L (ppb)	Ba µg/L (ppb)	Cd µg/L (ppb)	Cr µg/L (ppb)	Hg µg/L (ppb)	Pb µg/L (ppb)	Se µg/L (ppb)
TCLP Regulatory Limit	5000	5000	100 000	1000	5000	200	5000	1000
Virginia DOT	NA ^A	NA	NA	1.55	2.8	NA	19.6	NA
Scrap Tire Management ^B	ND ^C	2	590	ND	48	0.4	16	ND
Maine	ND	ND	357	185	84	ND	216	ND

^A NA = not available, that is, not measured or not reported for that study.

^B Maximum value reported for the seven tire products that were tested.

^C ND = non-detect.

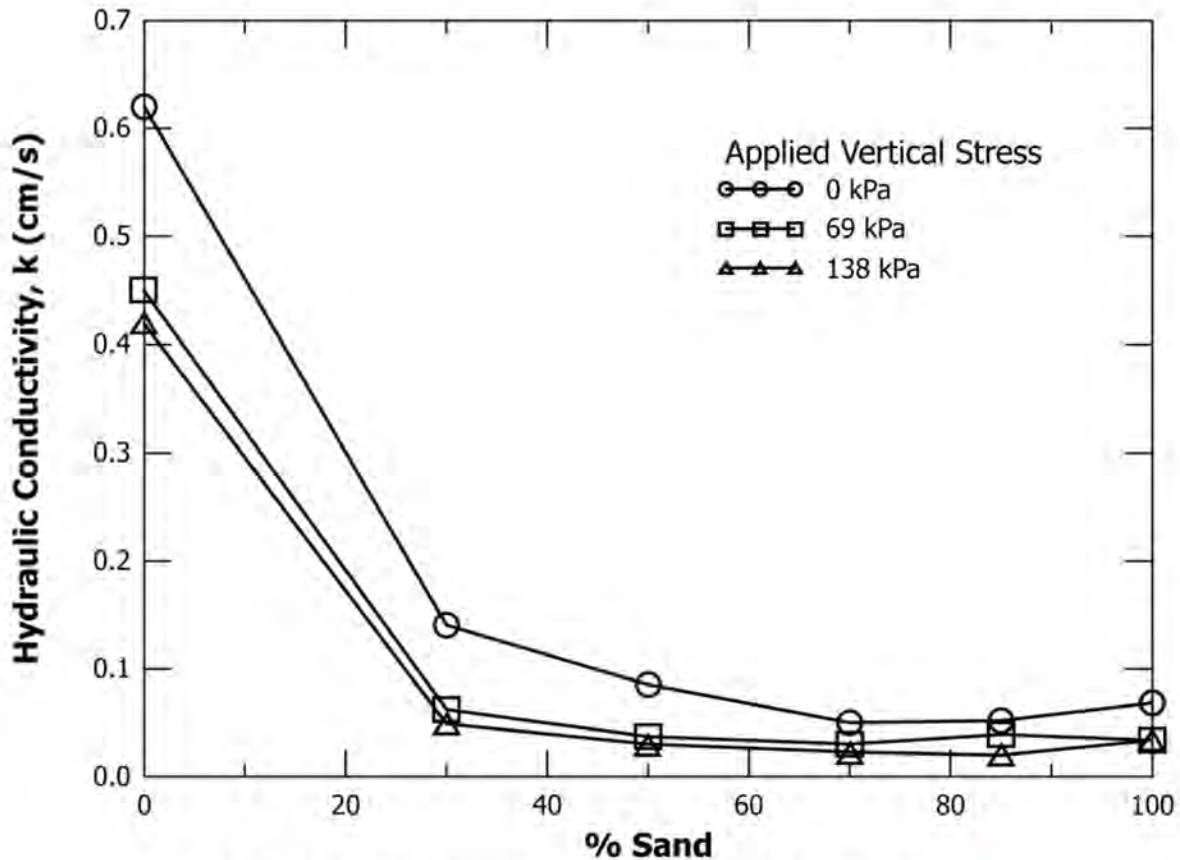


FIG. X1.5 Hydraulic Conductivities of Mixtures of TDA and Clean Sand (4)

TABLE X1.20 Mean Concentrations of Inorganic Analytes with Primary Drinking Water Standards from Field Studies with Direct Collection of Samples (33)

NOTE 1—When possible, the calculated mean is reported; if the mean could not be calculated because of limited number of samples with concentrations above the detection limit, then the percent of the results below the detection limit is reported.

Analyte	RAL	PRG	Wisconsin		North Yarmouth			Witter Farm Road ^A	Ohio Monofills		Binghamton, NY	
			West 4 th TDA	East 2 nd TDA	Control	TDA Section C	TDA Section D		C&E Monofill	American Monofill	Control TF2	TDA TF1
antimony (Sb)	0.006	0.015	NA	NA	100 % <0.05 ^B	100 % <0.05 ^B	NA	NA	0.1290	100 % <0.005	NA	NA
arsenic (As)	0.010	4.5 × 10 ⁻⁵	NA	NA	NA	NA	NA	NA	0.31	67 % <0.001	NA	NA
barium (Ba)	2.0	2.6	0.346	0.281	0.0688	0.0339	0.0395	0.017	0.218	0.0603	0.796	0.392
beryllium (Be)	0.004	0.073	NA	NA	100 % <0.005 ^B	100 % <0.005 ^B	NA	NA	100 % <0.1	100 % <0.001	NA	NA
cadmium (Cd)	0.005	0.018	NA	NA	95 % <0.0005	100 % <0.0005	96 % <0.0005	<0.0005	80 % <0.1	67 % <0.001	0.0325	0.00867
chromium (Cr)	0.1	0.11	NA	NA	0.0118	0.0126	0.0119	<0.006	NA	NA	NA	NA
copper (Cu)	1.3	1.5	NA	NA	91 % <0.009	91 % <0.009	96 % <0.009	<0.009	80 % <0.02	67 % <0.01	NA	NA
fluoride (F)	4.0	2.2	NA	NA	NA	NA	NA	NA	0.8018	0.7356	NA	NA
lead (Pb)	0.015	NL	90 % <0.003	0.008	88 % <0.002	88 % <0.002	94 % <0.002	<0.002	0.19	67 % <0.001	NA	NA
mercury (Hg)	0.002	0.011	NA	NA	100 % <0.0005 ^B	100 % <0.0005 ^B	NA	NA	NA	NA	NA	NA
nitrate (NO ₃ ⁻)	10	10	NA	NA	NA	NA	NA	NA	0.9217	0.8933	NA	NA
selenium (Se)	0.05	0.018	NA	NA	NA	NA	NA	NA	0.231	100 % <0.001	NA	NA
thallium (Tl)	0.002	0.0024	NA	NA	NA	NA	NA	NA	80 % <0.002	100 % <0.002	NA	NA

^A Results from a single sample reported.

^B Results from two unfiltered samples reported by Exponent (60); results for TDA are a composite sample of TDA sections C and D.

Units = mg/L.

NA = Not available—parameter not tested for.

NL = Preliminary remediation goal for tap water not listed for this analyte.

Refs: Wisconsin (34, 61); North Yarmouth (35, 60); Witter Farm Road (37); Ohio Monofills (38); Binghamton (39); RAL (62); PRG (32).

TABLE X1.21 Mean Concentrations of Inorganic Analytes with Secondary Drinking Water Standards from Field Studies with Direct Collection Of Samples (33)

NOTE 1—When possible, the calculated mean is reported; if the mean could not be calculated because of limited number of samples with concentrations above the detection limit, then the percent of the results below the detection limit is reported.

Analyte	Secondary Standard	PRG	Wisconsin		North Yarmouth			Witter Farm Road ^A	Ohio Monofills		Binghamton, NY	
			West 4 th TDA	East 2 nd TDA	Control	TDA Section C	TDA Section D		C&E Monofill	American Monofill	Control TF2	TDA TF1
aluminum (Al)	0.2	36	NA	NA	81 % <0.07	100 % <0.07	100 % <0.07	<0.07	7.97	67 % <0.1	NA	NA
chloride (Cl ⁻)	250	NL	477	600	345.8 ^B	331.9 ^B	338 ^B	111	44.2	34.6	NA	NA
copper (Cu)	1	1.5	NA	NA	91 % <0.009	91 % <0.009	96 % <0.009	<0.009	80 % <0.02	67 % <0.01	NA	NA
fluoride (F)	2.0	2.2	NA	NA	NA	NA	NA	NA	0.80	0.736	NA	NA
iron (Fe)	0.3	11	0.71	1.13	0.0198	0.0795	0.555	0.158	0.19	0.103	0.255	15.0
manganese (Mn)	0.05	0.88	1.129	1.522	0.0421	4.38	2.56	2.53	2.72	1.93	0.260	6.21
silver (Ag)	0.10	0.18	NA	NA	NA	NA	NA	NA	80 % <0.005	100 % <0.001	NA	NA
sulfate (SO ₄ ²⁻)	250	NL	115	213	25.3 ^B	18.9 ^B	11.4 ^B	3.51	468.5	600.7	NA	NA
zinc (Zn)	5	11	0.093	0.230	1.10	0.0111	0.0111	0.082	0.492	100 % <0.005	0.300	0.0343

^A Results from a single sample reported.

^B Results for unfiltered sample reported.

Units = mg/L.

NA = Not available—parameter not tested for.

NL = Preliminary remediation goal for tap water not listed for this analyte.

References: Wisconsin (34, 61); North Yarmouth (35, 60); Witter Farm Road (37); Ohio Monofills (38); Binghamton (39); Secondary Standard (62); PRG (32).

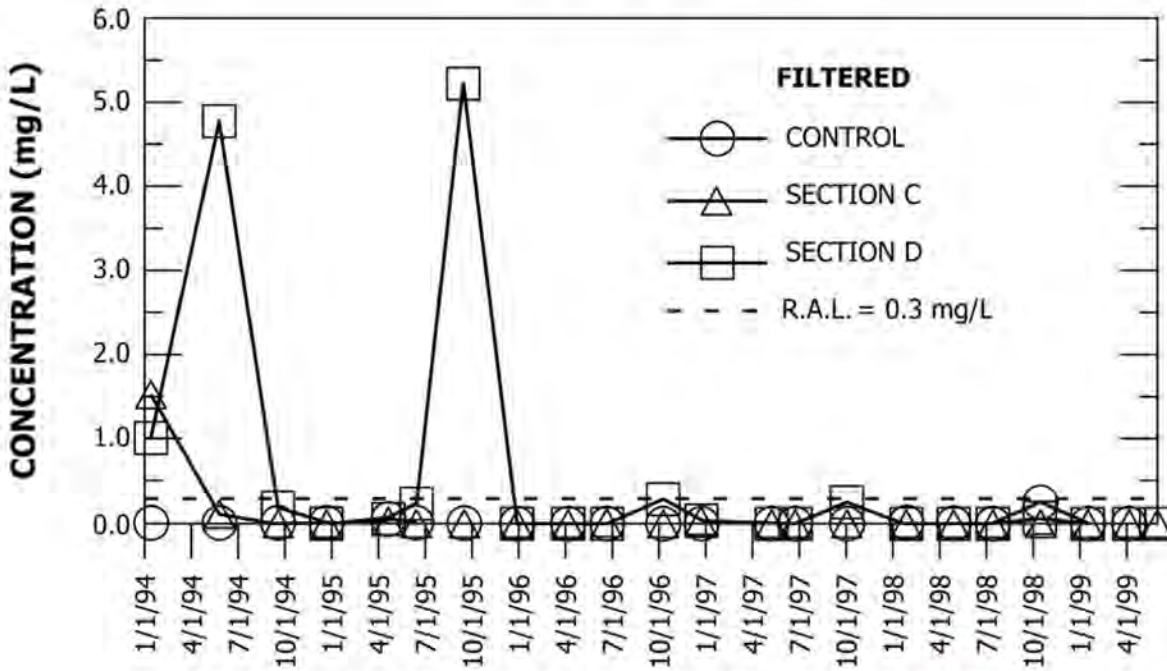


FIG. X1.6 Iron Levels for Filtered Samples at North Yarmouth Field Trial (35)

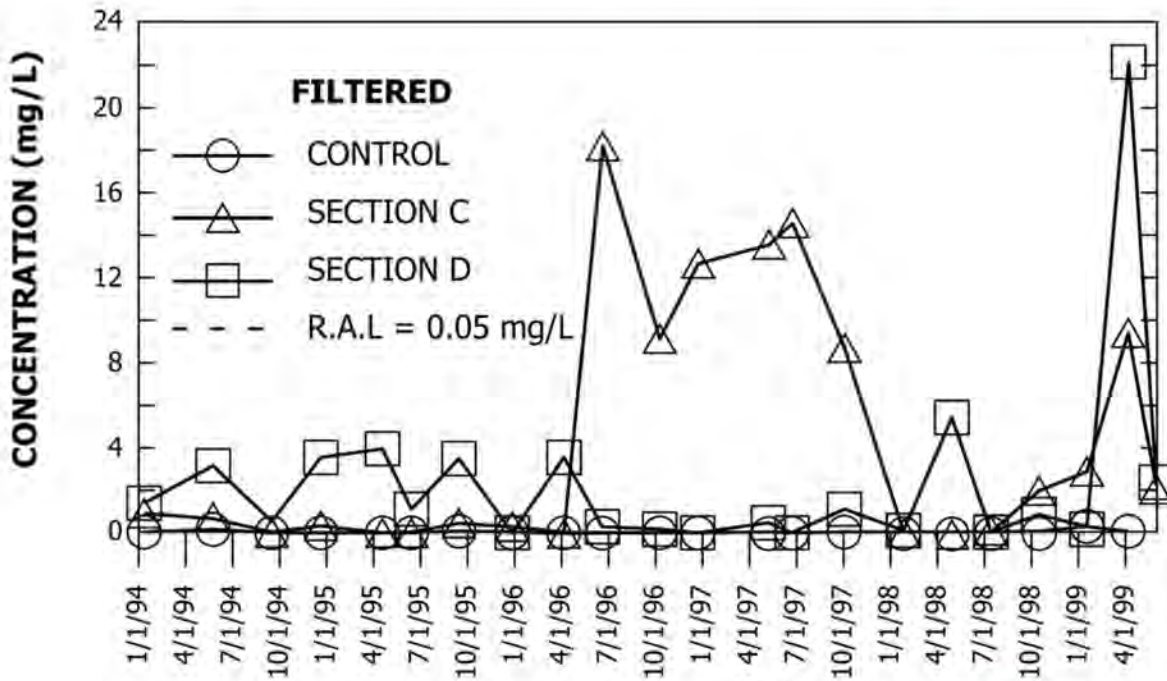


FIG. X1.7 Manganese Levels for Filtered Samples at North Yarmouth Field Trial (35)

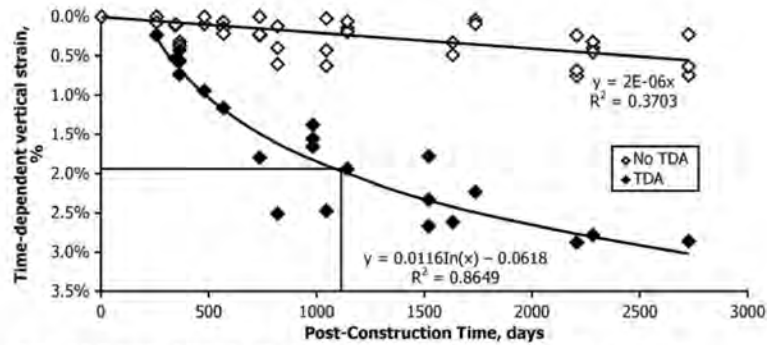


FIG. X1.8 Time-Dependent Settlement Curve for a 4.6-m TDA Fill

REFERENCES

- (1) Humphrey, D. N., "Investigation of Exothermic Reaction in TDA Fill Located on SR 100 in Ilwaco, Washington," Report to the Federal Highway Administration, Washington, DC, March 1996.
- (2) Ad Hoc Civil Engineering Committee, "Design Guidelines to Minimize Internal Heating of TDA Fills," Scrap Tire Management Council, Washington, DC, 1997, (revised 2002).
- (3) Humphrey, D. N. and Manion, W. P., "Properties of Tire Chips for Lightweight Fill," *Grouting, Soil Improvement, and Geosynthetics*, ASCE, Vol 2, 1992, pp. 1344–55.
- (4) Edil, T. B. and Bosscher, P. J., "Development of Engineering Criteria for Shredded or Whole Tires in Highway Applications," Report No. WI 14-92, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, WI, November 1992.
- (5) Ahmed, I., "Laboratory Study on Properties of Rubber Soils," Report No. FHWA/IN/JHRP-93/4, Purdue University, West Lafayette, IN, 1993.
- (6) Ahmed, I. and Lovell, C. W., "Rubber Soils as Lightweight Geomaterial," *Transportation Research Record*, No. 1422, 1993, pp. 61–70.
- (7) Tweedie, J., Humphrey, D. N., and Sandford, T. C., "Tire Chips as Lightweight Backfill for Retaining Walls-Phase II, Field Trial," a study for the New England Transportation Consortium, Department of Civil Engineering, University of Maine, Orono, ME, 1997.
- (8) Ahn, I. S., Cheng, L., Fox, P. J., Wright, J., Patenaude, S., and Fujii, R., "Material Properties of Large-Size Tire Derived Aggregate for Civil Engineering Applications," *Journal of Materials in Civil Engineering*, Vol 27, No. 9, 2015.
- (9) Wartman, J., Natale, M., and Strenk, P., "Immediate and Time-Dependent Compression of Tire Derived Aggregate," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol 133, No. 3, 2007, pp. 245–56.
- (10) Tweedie, J. J., Humphrey, D. N., and Sandford, T. C., "Tire Shreds as Retaining Wall Backfill, Active Conditions," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol 124, No. 11, 1998, pp. 1061–70.
- (11) Nickels, Jr., W. L. and Humphrey, D. N., "The Effect of Tire Chips as Subgrade Fill on Paved Roads," Technical Services Division, Maine Department of Transportation, Augusta, ME, 1997.
- (12) Tweedie, J. J., Humphrey, D. N., and Sandford, T. C., "Full Scale Field Trials of Tire Chips as Lightweight Retaining Wall Backfill, At-Rest Conditions," *Transportation Research Record* No. 1619, Transportation Research Board, Washington, DC, 1998, pp. 64–71.
- (13) McCartney, J. S., Ghaaowd, I., Sanders, M., and Fox, P. J., "Large Scale Measurement of Internal and Interface Shear Strength of Tire Derived Aggregate—Phase II," prepared by the University of California San Diego, Jacobs School of Engineering, Department of Structural Engineering, for California Department of Resources Recycling and Recovery, 2015.
- (14) Humphrey, D. N., Chen, L. H., and Lawrence, B. K., "Use of Tire Chip/Soil Mixtures to Limit Frost Heave and Pavement Damage of Paved Roads," a study for the New England Transportation Consortium, Department of Civil Engineering, University of Maine, Orono, ME, 1998.
- (15) Cosgrove, T. A., "Interface Strength Between Tire Chips and Geomembrane for Use as a Drainage Layer in a Landfill Cover," *Proceedings of Geosynthetics '95*, Vol 3, Industrial Fabrics Association, St. Paul, MN, 1995, pp. 1157–68.
- (16) "Report on Caltrans Wall 207 Instrumentation Project I-215/Route 60 & Route 91 Interchange Riverside, California," prepared by Haley & Aldrich, Inc. for Dana N. Humphrey/CalRecycle, January 2009.
- (17) Ahn, I. S. and Cheng, L., "Tire Derived Aggregate for Retaining Wall Backfill Under Earthquake Loading," *Construction and Building Materials*, Vol 57, 2014, pp. 105–16.
- (18) Jeremić, B., Putnam, J., Sett, K., Humphrey, D., and Patenaude, S., "Calibration of Elastic-Plastic Material Model for Tire Shreds," *GeoTrans 2004*, American Society of Civil Engineers, Reston, VA, 2004.
- (19) Wright, J., Vossler, D. J., and Crawford, R., "Badlands Landfill Tire Derived Aggregate Gas Collection: Pilot Analysis Phase III Report," prepared by GHD, Inc. for CalRecycle, August 2013, <http://www.calrecycle.ca.gov/tires/TDA/Projects/Badlands.htm>.
- (20) Wolfe, S. L., Humphrey, D. N., and Wetzel, E. A., "Development of Tire Shred Underlayment to Reduce Groundborne Vibration from LRT Track," *Geotechnical Engineering for Transportation Projects: Proceedings of GeoTrans 2004*, ASCE, 2004, pp. 750–59.
- (21) Wolfe, S. L., "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track—Results of 2005 Field Tests," prepared by Wilson, Ihrig & Associates, Inc. for Dana N. Humphrey, Consulting Engineer/CalRecycle, Final Report, March 2006.
- (22) Wolfe, S. L., "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track—Results of 2006 Field Tests," prepared by Wilson, Ihrig & Associates, Inc. for Dana N. Humphrey, Consulting Engineer/CalRecycle, Final Report, February 2007.
- (23) Wolfe, S. L., "Evaluation of Tire Derived Aggregate as Installed Beneath Ballast and Tie Light Rail Track—Results of 2009 Field Tests," prepared by Wilson, Ihrig & Associates, Inc. for Dana N. Humphrey, Consulting Engineer/CalRecycle, Final Report, June 2009.
- (24) Finney, B., "Exothermic Behavior of Tire Derived Aggregate Fill Subject to Periodic Wetting with Fresh and Saline Water," prepared by Humboldt State University, Department of Environmental Resources Engineering, for California Department of Resources Recycling and Recovery, June 2018.

- (25) Humphrey, D. N., "Effectiveness of Design Guidelines for use of Tire Derived Aggregate as Lightweight Embankment Fill," *Recycled Materials In Geotechnics*, ASCE, 2004, pp. 61–74.
- (26) Finney, B. "Properties of Tire Derived Aggregate for Civil Engineering Applications," prepared by Humboldt State University for CalRecycle, May 2013.
- (27) Cheng, D. X., "Evaluation of Gradation Specification of Tire Derived Aggregate in California," prepared by the California State University, TDA Technology Center, for California Department of Resources Recycling and Recovery, September 2016.
- (28) Zelibor, J. L., "Leachate from Scrap Tires: RMA TCLP Report," *Education Seminar on Scrap Tire Management*, Scrap Tire Management Council, Washington, DC, September 1991, pp. 381–91.
- (29) Ealding, W., "Final Report on Leachable Metals in Scrap Tires," Virginia Department of Transportation Materials Division, Virginia Department of Transportation Scrap Tire Task Force, 1992.
- (30) Downs, L. A., Humphrey, D. N., Katz, L. E., and Rock, C. A., "Water Quality Effects of Using Tire Chips Below the Groundwater Table," a report prepared by the Department of Civil and Environmental Engineering, University of Maine, Orono, ME, for the Maine Department of Transportation, 1997.
- (31) Twin City Testing, "Environmental Study of the Use of Shredded Waste Tires for Roadway Sub-Grade Support," Twin City Testing Corp., St. Paul, MN, Waste Tire Management Unit, Site Response Section, Groundwater and Solid Waste Division, Minnesota Pollution Control Agency, St. Paul, MN, February 1990.
- (32) USEPA, "Preliminary Remediation Goals," Region 9, U.S. Environmental Protection Agency, San Francisco, CA, 2004, <http://www.epa.gov/region09/waste/sfund/prg/#prgtable>.
- (33) Humphrey, D. N. and Swett, M., "Literature Review of the Water Quality Effects of Tire Derived Aggregate and Rubber Modified Asphalt Pavement," Dept. of Civil and Environmental Engineering, University of Maine, Orono, ME, for U.S. Environmental Protection Agency Resource Conservation Challenge, November 29, 2006.
- (34) Bosscher, P. J., Edil, T. B., and Eldin, N. N., "Construction and Performance of a Shredded Waste Tire Test Embankment," *Transportation Research Record*, No. 1345, Transportation Research Board, Washington, DC, 1993, pp. 44–52.
- (35) Humphrey, D. N. and Katz, L. E., "Five-Year Field Study of the Effect of Tire Shreds Placed Above the Water Table on Groundwater Quality," *Transportation Research Record*, No. 1714, Transportation Research Board, Washington, DC, 2000, pp. 18–24.
- (36) Sheehan, P. J., Warmerdam, J. M., Ogle, S., Humphrey, D. N., and Patenaude, S. M., "Evaluating the Toxicity of Leachate from Tire Shred Fill in Roads and the Risk to Aquatic Ecosystems," *Journal of Environmental Toxicology and Chemistry*, Vol 25, No. 2, 2006, pp. 400–11.
- (37) Humphrey, D. N., "Water Quality Results for Whitter Farm Road Tire Shred Field Trial," Dept. of Civil and Environmental Engineering, University of Maine, Orono, ME, 1999.
- (38) Chyi, L. L., "Shredded Tire Leachate from Monofill Sites," Department of Geology, University of Akron, 2000.
- (39) Brophy, M. and Graney, J., "Groundwater Effects from Highway Tire Shred Use," *Environmental Forensics*, Vol 5, No. 2, 2004, pp. 79–84.
- (40) Humphrey, D. N. and Katz, L. E., "Water Quality Testing for Dingley Road Tire Chip Test Project," a report for the Town of Richmond, Maine, by Department of Civil and Environmental Engineering, University of Maine, Orono, ME, 1995.
- (41) Hoppe, E. J. and Mullen, W. G., "Field Study of a Shredded-Tire Embankment in Virginia—Final Report," Report No. VTRC 04-R20, Virginia Transportation Research Council, Charlottesville, VA, 2004.
- (42) Helsel, D. R., *Nondetects and Data Analysis*, John Wiley & Sons, Hoboken, NJ, 2005.
- (43) Finney, B. and Maeda, R. K. "Evaluation of Tire Derived Aggregate as a Media for Stormwater Treatment," prepared by Humboldt State University for CalRecycle, April 2016.
- (44) Edil, T. B., Park, J. K., and Kim, J. Y., "Effectiveness of Scrap Tire Chips as Sorptive Drainage Material," *Journal of Environmental Engineering*, Vol 130, No. 7, 2004, pp. 824–31.
- (45) Humphrey, D. N. and Katz, L. E., "Field Study of the Water Quality Effects of Tire Shreds Placed Below the Water Table," *Proceedings of the International Conference on Beneficial Use of Recycled Materials in Transportation Applications*, Arlington, VA, 2001, pp. 699–708.
- (46) Humphrey, D. N., Sandford, T. C., Cribbs, M. M., Gharegrat, H., and Manion, W. P., "Tire Chips as Lightweight Backfill for Retaining Walls—Phase I," a study for the New England Transportation Consortium, Department of Civil Engineering, University of Maine, Orono, ME, 1992.
- (47) Manion, W. P. and Humphrey, D. N., "Use of Tire Chips as Lightweight and Conventional Embankment Fill, Phase I—Laboratory," Technical Paper 91-1, Technical Services Division, Maine Department of Transportation, Augusta, ME, 1992.
- (48) Bressette, T., "Used Tire Material as an Alternative Permeable Aggregate," Report No. FHWA/CA/TL-84/07, Office of Transportation Laboratory, California Department of Transportation, Sacramento, CA, 1984.
- (49) Humphrey, D. N. and Sandford, T. C., "Tire Chips as Lightweight Subgrade Fill and Retaining Wall Backfill," *Proceedings of the Symposium on Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities*, Federal Highway Administration, Washington, DC, 1993, pp. 5–87 to 5–99.
- (50) Strenk, P. M., Warman, J., Grubb, D. G., Humphrey, D. N., and Natale, M. F., "Variability and Scale-Dependency of Tire Derived Aggregate," *Journal of Materials in Civil Engineering*, Vol 19, No. 3, 2007, pp. 233–41.
- (51) Edil, T. B. and Bosscher, P. J., "Engineering Properties of Tire Chips and Soil Mixtures," *Geotechnical Testing Journal*, Vol 17, No. 4, 1994, pp. 453–64.
- (52) Drescher, A. and Newcomb, D. E., "Development of Design Guidelines for Use of Shredded Tires as a Lightweight Fill in Road Subgrade and Retaining Walls," Report No. MN/RC-94/04, Department of Civil and Mineral Engineering, University of Minnesota, Minneapolis, MN, 1994.
- (53) Shao, J., Zarling, J. P., and ESCH, D., "Thermal Conductivity of Recycled Tire Rubber for Insulation Beneath Roadways," Transportation Research Board, 1995.
- (54) Humphrey, D. N., Sandford, T. C., Cribbs, M. M., Gharegrat, H., and Manion, W. P., "Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill," *Transportation Research Record*, No. 1422, Transportation Research Board, 1993, pp. 29–35.
- (55) McCartney, J. S. and Ghaaowd, I., "Evaluation of Geosynthetic Pullout Strength and Soil Interface Shear Strength for Tire Derived Aggregate with Large Particle Size—Phase III," prepared by the University of California San Diego, Jacobs School of Engineering, Department of Structural Engineering, for California Department of Resources Recycling and Recovery, May 2018.
- (56) Hannon, J. B. and Forsyth, R. A., "Fill Stabilization Using Nonbiodegradable Waste Products—Phase I," Report No. CA-DOT-TL-2124-1-72-25, Transportation Laboratory, California Department of Transportation, Sacramento, CA, August 1973.
- (57) Benson, C. H. and Khire, M. V., "Closure to: Reinforcing Sand with Strips of Reclaimed High-Density Polyethylene," *Journal of Geotechnical Engineering*, Vol 121, No. 4, 1995, pp. 400–01.
- (58) Hall, T. J., "Reuse of Shredded Waste Tire Material for Leachate Collection Systems at Municipal Solid Waste Landfills," for Iowa Department of Natural Resources Waste Management and Authority Division, by Shive-Hattery Engineers and Architects, Inc.
- (59) Humphrey, D. N., Chen, L. H., and Eaton, R. A., "Laboratory and Field Measurement of the Thermal Conductivity of Tire Chips for Use as Subgrade Insulation," Preprint No. 971289, Transportation Research Board, Washington, DC, 1997.

- (60) Exponent, Inc., "Tire Shred Leachate Study: Chemical Composition and Aquatic Toxicity for Above- and Below-Water-Table Applications," report prepared for California Integrated Waste Management Board, Oakland, California, 2003.
- (61) Eldin, N. N. and Senouci, A. B., "Use of Scrap Tires in Road Construction," *Journal of Construction Engineering and Management*, Vol 118, No. 3, 1992, pp. 561-76.
- (62) USEPA, "Drinking Water Contaminants Website," last updated on November 3, 2006, U.S. Environmental Protection Agency, Washington, DC, <http://www.epa.gov/safewater/mcl.html>.
- (63) Wright, J., "TDA Slide Repair Settlement Report: Analysis of Marina Drive, Geysers Road, Sonoma Mountain Road, and Palomino Road Repair Projects," prepared by GHD Inc. for CalRecycle, January 2016.
- (64) Benda, C. C., "Engineering Properties of Scrap Tires Used in Geotechnical Applications," Report 95-1, Materials and Research Division, Vermont Agency of Transportation, Montpelier, VT, 1995.
- (65) "CIWMB 06008 TDA Sample Summary Report," prepared by Kenec for California Integrated Waste Management Board, March 2009.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; <http://www.copyright.com/>

<i>Inorganic Parameters: Totals, unfiltered</i>			
<i>units:</i> <i>µg/L</i>	COD	CaC O3	TDS
Standard	N/A	N/A	N/A
May-20	18.2	7.85	186
Jul-20	47.9	51.8	310
Oct-20	30.8	21.5	194
Apr-21	17.2	13.2	122
Jul-21	25.6	29.2	166
Nov-21	<15	94.5	NS
*Surface water standard			