**Designation: D6270 − 20**

# Standard Practice for
# Use of Scrap Tires in Civil Engineering Applications[1]

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 reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

## 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/ft$^3$ (600 kN-m/m$^3$))

D1557 Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft$^3$ (2,700 kN-m/m$^3$))

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D3080/D3080M Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions (Withdrawn 2020)[3]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 Soils[4]

M 288 Standard Specification for Geotextiles[5]

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

Method 1311 Toxicity Characteristics Leaching Procedure[6]

## 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)**

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[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.

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[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 ($\rho_s$) 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
$\rho_w$ = 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 % × 600 kN-m/m$^3$ = 360 kN-m/m$^3$) to 100 % of Test Methods D1557 (2700 kN-m/m$^3$) 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

**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.

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

volume of 0.0125 $m^3$ 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 uncompressed 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**):

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

where:

$\sigma v$ = vertical stress, and
$\gamma$ = compacted unit weight, $kN/m^3$.

5.3.4 Time-dependent settlement for an average duration of four weeks, $\Delta H_t$, can be calculated as (**9**):

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

where:

$C_{\alpha\varepsilon}$ = 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

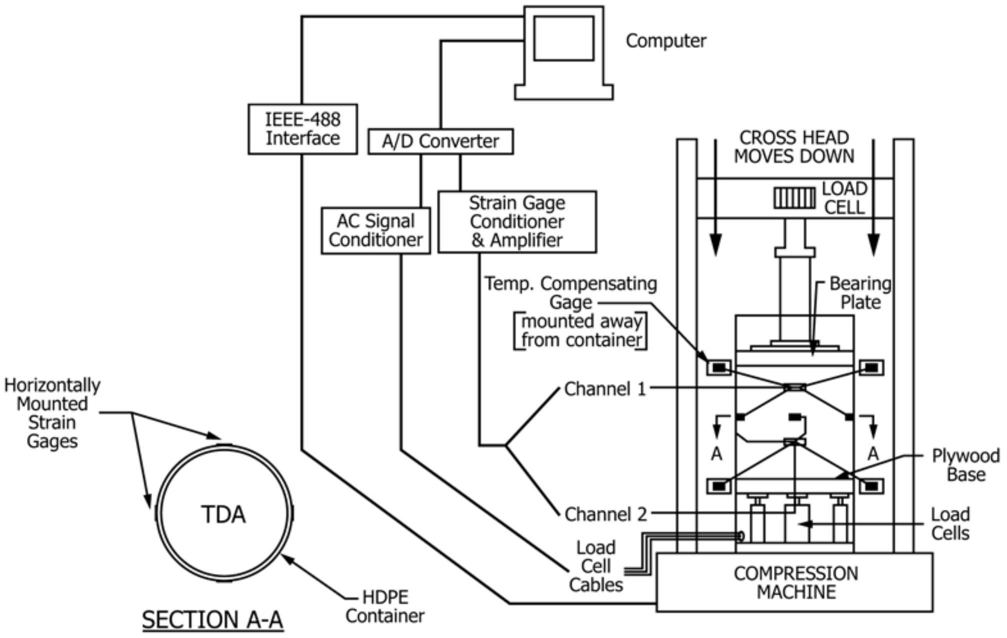

FIG. 1 Compressibility Apparatus for TDA Designed to Measure Lateral Stress and the Portion of the Vertical Load Transferred by Friction from TDA to Container (11)

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:

$$M_R = A\theta^B \tag{4}$$

where:

$\theta$ = 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:

$$K_0 = \frac{\sigma_h}{\sigma_v} \tag{5}$$

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

where:

$\sigma_h$ = measured horizontal stress, and
$\sigma_v$ = 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

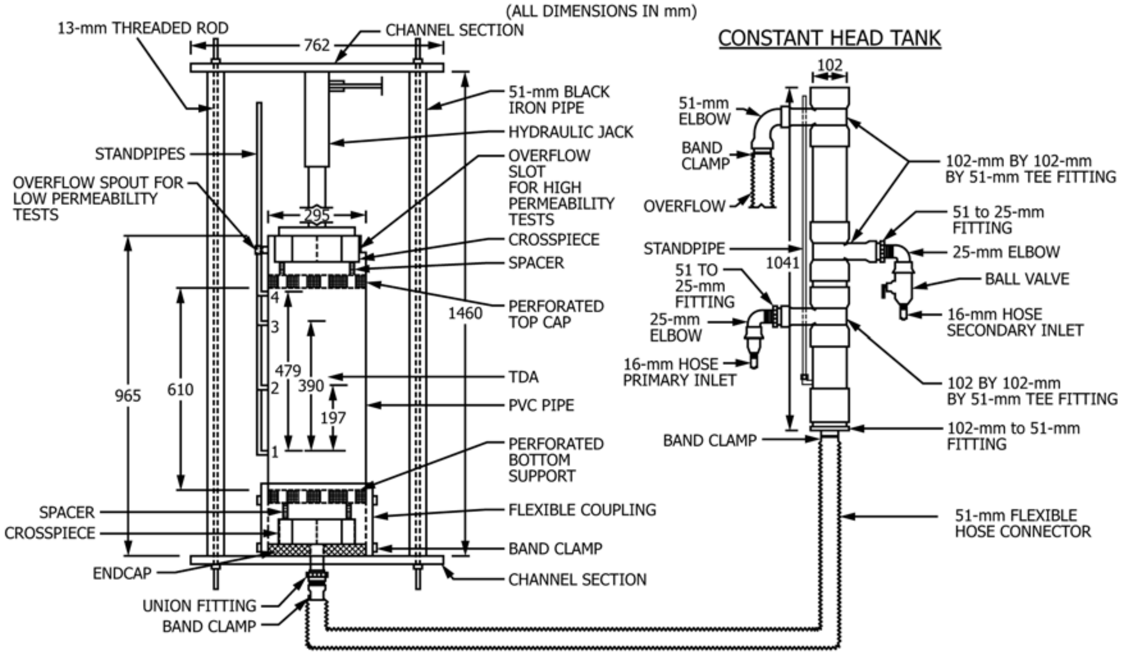

**FIG. 2 Hydraulic Conductivity Apparatus for TDA with Provisions for Application of Vertical Stress (14)**

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 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.

**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 |

## 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 though 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 | 1.06 | 1.01 | 1.10 | 4 | (**47**) |
| Mixture | 1.06 | 1.16 | 1.18 | 9.5 | (**48**) |
| Mixture (Pine State) | - - - - | - - - - | 1.24 | 2 | (**46**) |
| Mixture (Palmer) | - - - - | - - - - | 1.27 | 2 | (**46**) |
| Mixture (Sawyer) | - - - - | - - - - | 1.23 | 4.3 | (**46**) |
| Mixture | 1.01 | 1.05 | 1.05 | 4 | (**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 | 4.80$^C$ | 6.11 | Cyclic loading with a maximum of 58 kPa | | |
| (OTR)$^D$ | | 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 | - - - - | Rodefeld | 594[B] | (4, 51) |
| Standard | 20 to 75 | - - - - | Rodefeld | 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 $kJ/m^3$.

60 % Standard = Impact compaction with compaction energy of 355.6 $kJ/m^3$.

Standard = Impact compaction with compaction energy of 296.4 $kJ/m^3$.

Modified = Impact compaction with compaction energy of 2693 $kJ/m^3$.

[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.

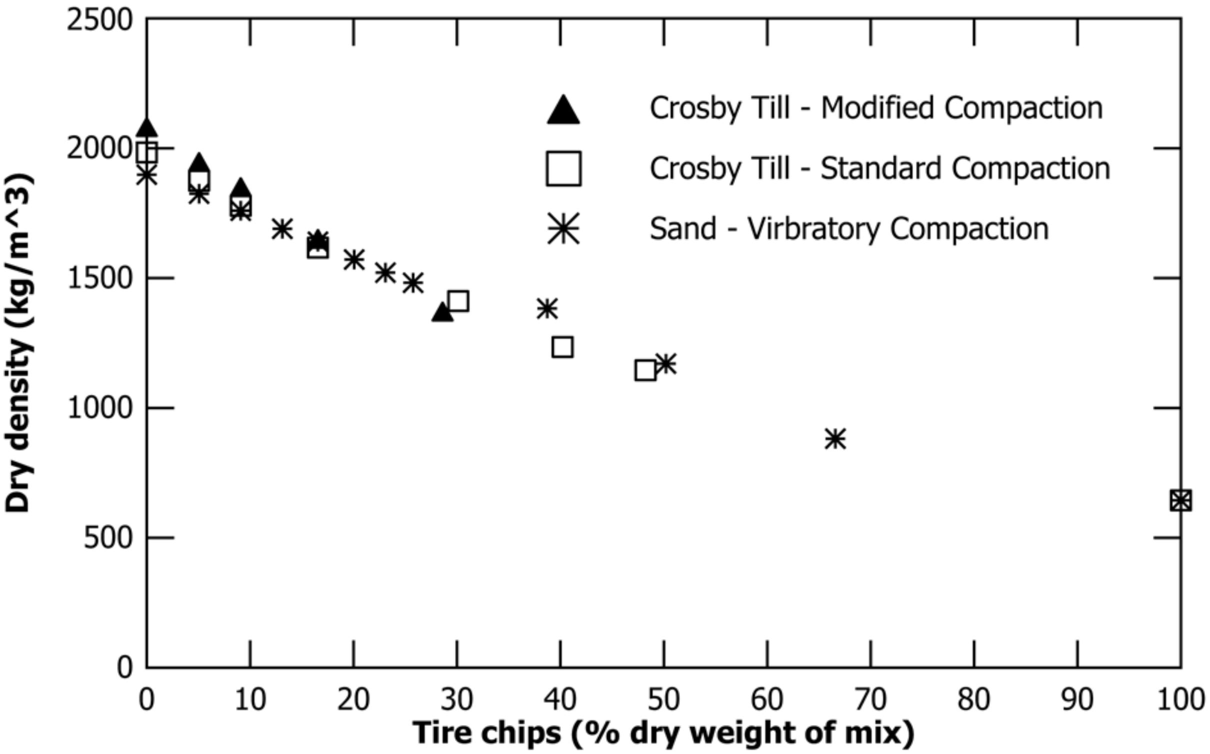

FIG. X1.1 Comparison of Compacted Dry Density of Mixtures of TDA with Ottawa Sand and Crosby Till (5)

## 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/m$^3$.

NOTE 3—The constants A and B assume the units for $\theta$ 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 | $K_O$ | -μ | 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.

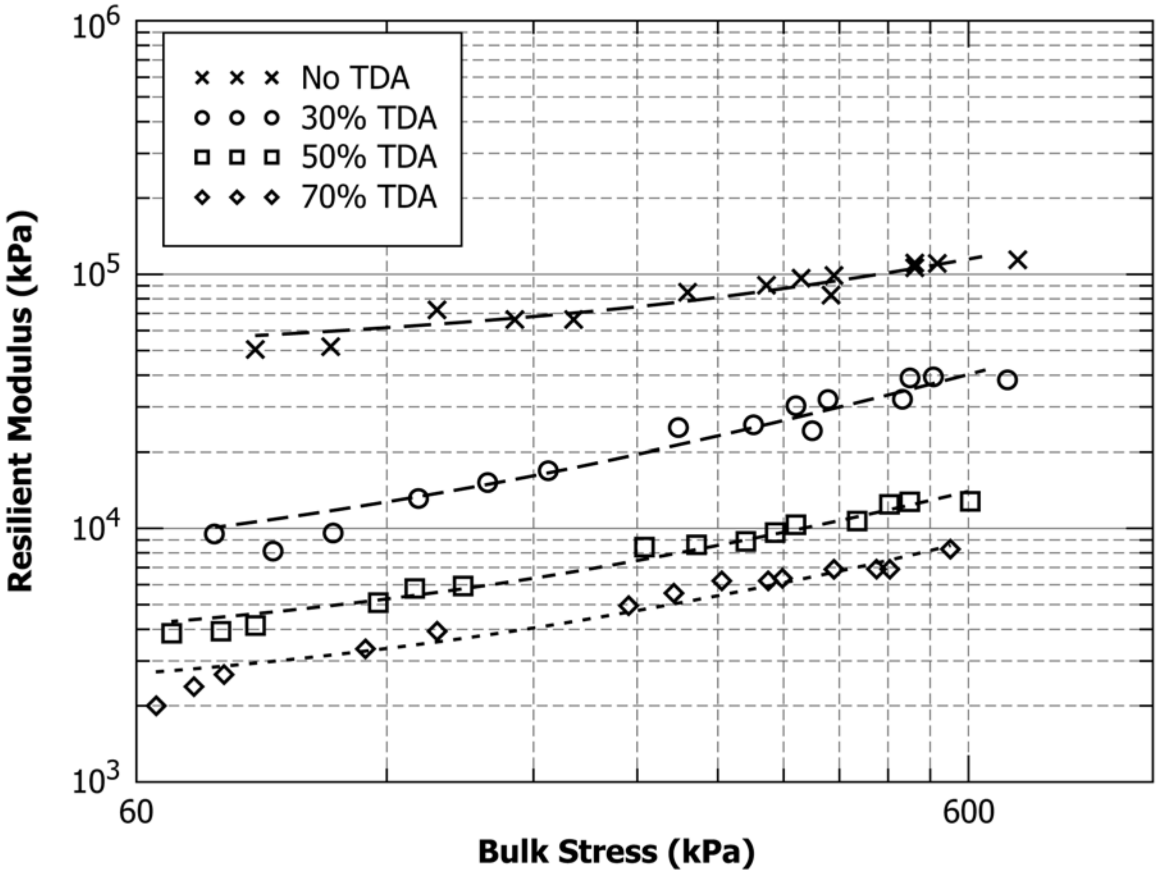

FIG. X1.2 Resilient Modulus of Mixtures of TDA and Clean Sand (4)

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, $\sigma_0$ (kPa) | Values at Peak Shear Strength | | | Average Dilation Angle, $\Psi$ (deg) |
|---|---|---|---|---|---|---|---|---|
| | | | | | $\sigma$ (kPa) | $\tau$ (kPa) | $\varphi_{sec}$ (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, $\sigma_0$ (kPa) | Values at Peak Shear Strength | | |
|---|---|---|---|---|---|---|---|
| | | | | | $\sigma$ (kPa) | $\tau$ (kPa) | $\varphi_{sec}$ (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, $\sigma_0$ (kPa) | Values At Peak Secant Friction Angle | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $\sigma$ (kPa) | $\tau$ (kPa) | $\varphi_{sec}$ (deg) | $\delta_f$ (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, $\sigma_0$ (kPa) | Values At Peak Secant Friction Angle | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $\sigma$ (kPa) | $\tau$ (kPa) | $\varphi_{sec}$ (deg) | $\delta_f$ (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, $\sigma_0$ (kPa) | Values At Peak Secant Friction Angle | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $\sigma$ (kPa) | $\tau$ (kPa) | $\varphi_{sec}$ (deg) | $\delta_f$ (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 |

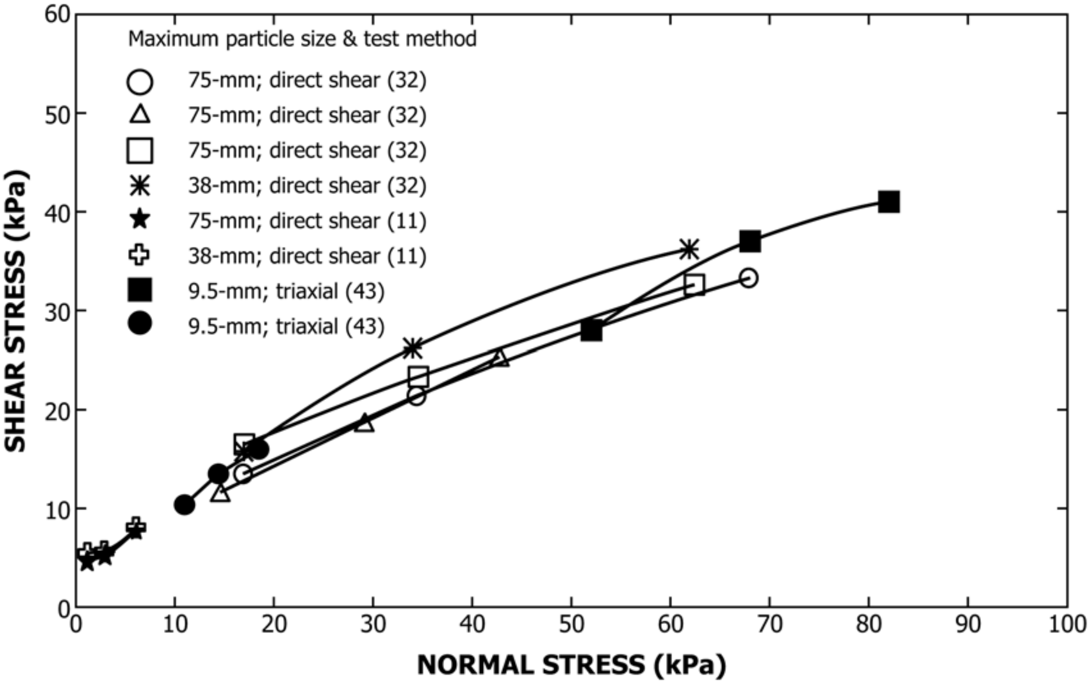

FIG. X1.3 Comparison of Failure Envelopes of TDA at Low Stress Levels

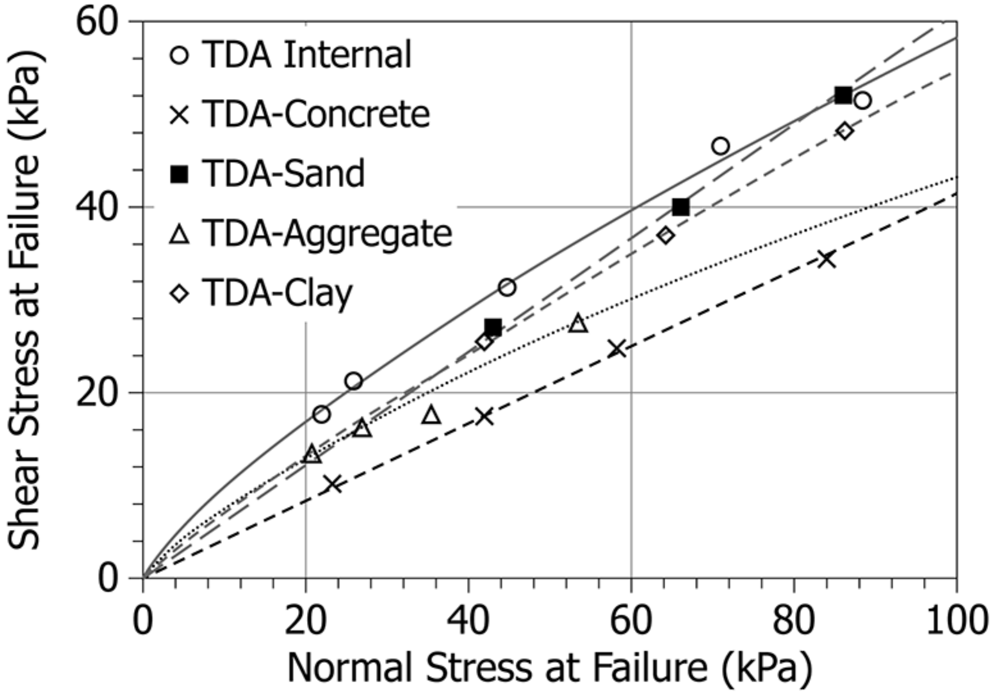

FIG. X1.4 Comparison of Failure Envelopes of TDA for All Interfaces at Low Stress Levels

### 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) | $\phi$ (°) |
|---|---|---|---|---|---|---|---|---|---|
| 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 α | $r^2$ | 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 | $1.6 \times 10^{-4}$ |
| 25 | Ottawa Sand | 15.5 | 1680 | $1.8 \times 10^{-3}$ |
| 25 | Ottawa Sand | 30.1 | 1530 | $3.5 \times 10^{-3}$ |
| 25 | Ottawa Sand | 37.7 | 1410 | $8.7 \times 10^{-3}$ |
| - - - - | Crosby till | 0 | 1910 | $8.9 \times 10^{-7}$ |
| 25 | Crosby till | 14.8 | 1700 | $1.8 \times 10^{-5}$ |
| 25 | Crosby till | 30.1 | 1390 | $2.1 \times 10^{-3}$ |
| 25 | Crosby till | 40 | 1200 | $8.8 \times 10^{-3}$ |
| 13 | Crosby till | 40 | 1190 | $9.7 \times 10^{-3}$ |

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 |
| Virigina 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.

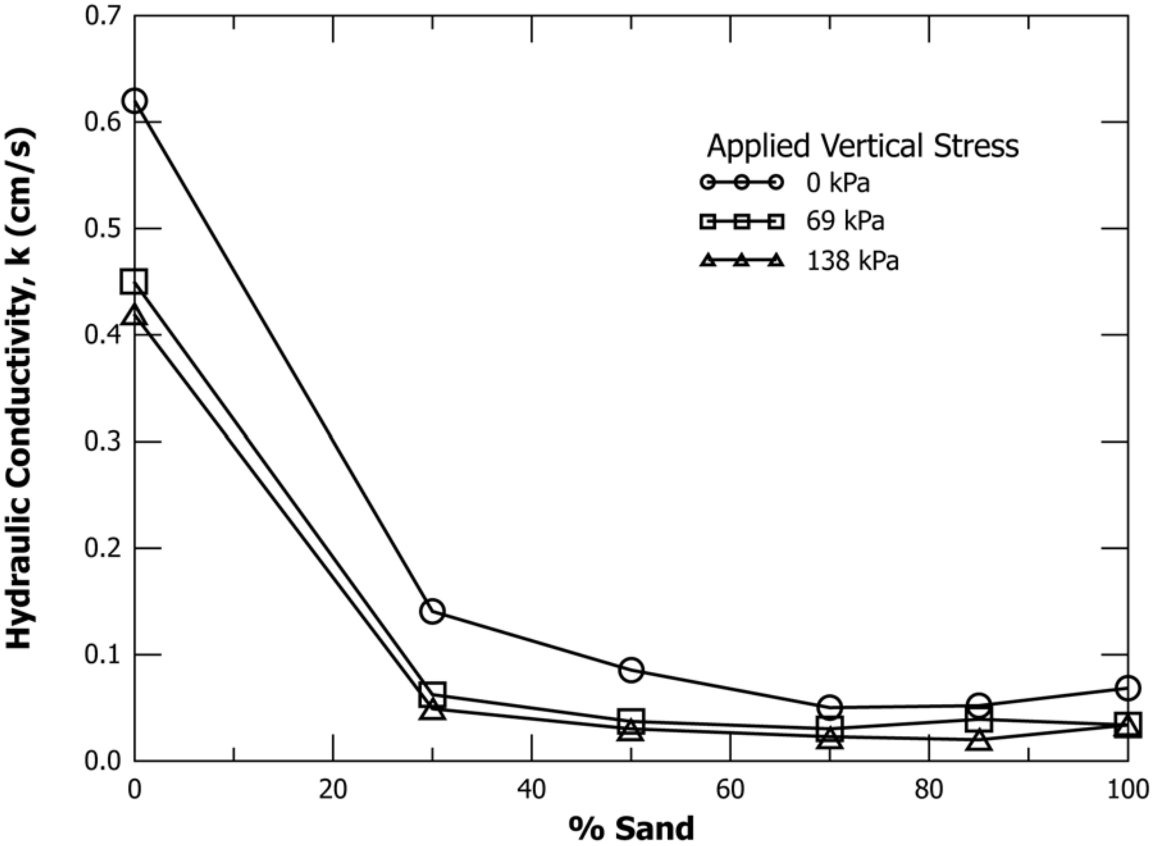

FIG. X1.5 Hydraulic Conductivities of Mixtures of TDA and Clean Sand (4)

### 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”TDA | East 2”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 | 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 | 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 |
| 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 (Ti) | 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”TDA | East 2”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).

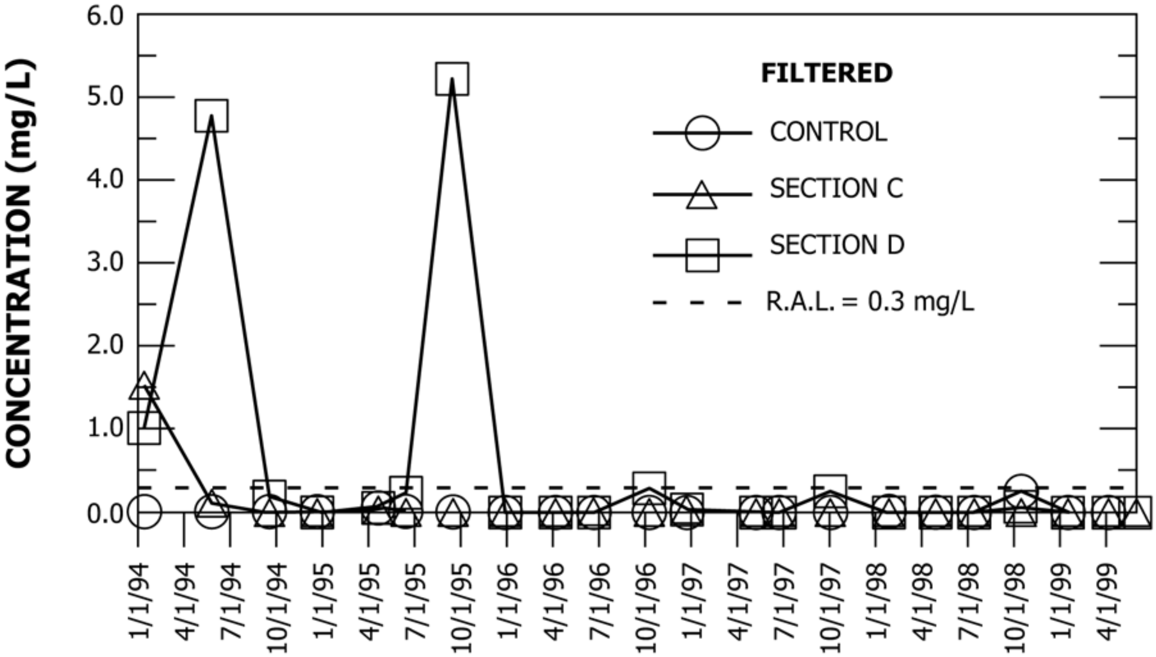

FIG. X1.6 Iron Levels for Filtered Samples at North Yarmouth Field Trial (35)

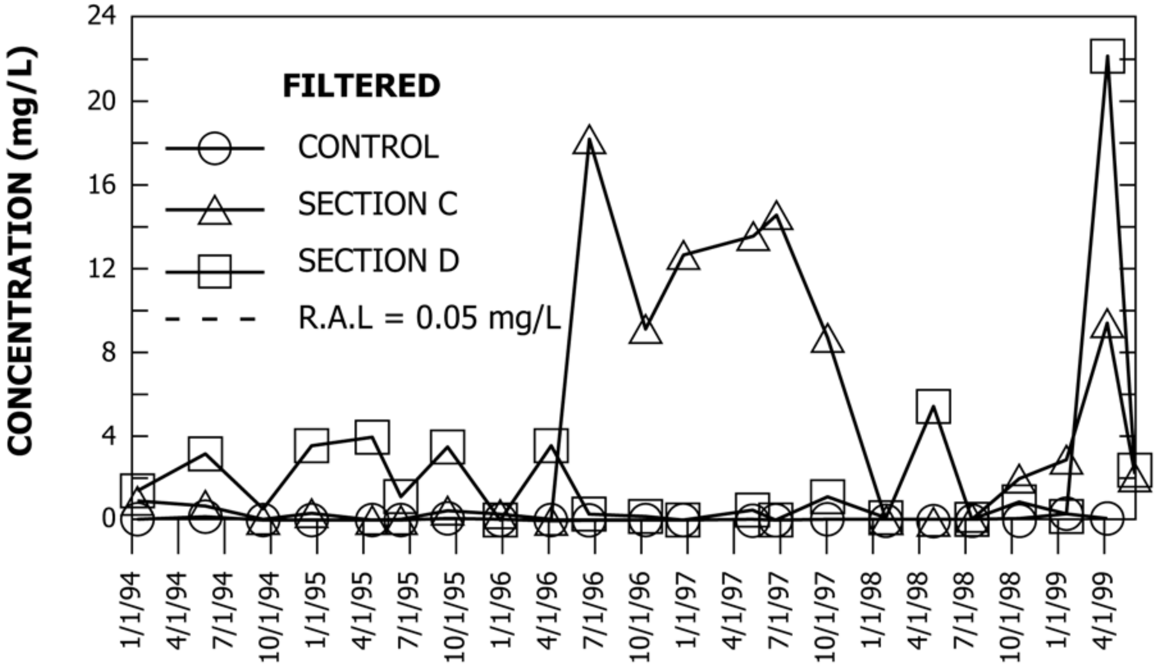

FIG. X1.7 Manganese Levels for Filtered Samples at North Yarmouth Field Trial (35)

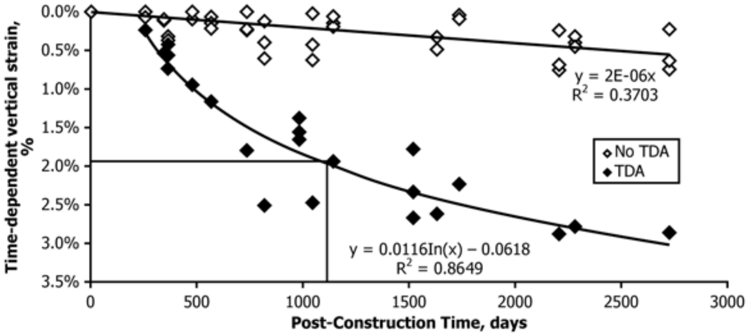

FIG. X1.8 Time-Dependent Settlement Curve for a 4.6-m TDA Fill

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