Guidance Manual

for Engineering Uses of Scrap Tires

Sponsored and Funded by:

Maryland Department of the Environment's
Scrap Tire Program

Geosyntec Project No.: ME0012-11
June 2008

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To Readers of this Manual:

The *Guidance Manual for Engineering Uses of Scrap Tires* was developed by Geosyntec Consultants working under contract for the Maryland Environmental Service (MES) and the Maryland Department of the Environment (MDE) with funding from the State's Scrap Tire Program. This provides guidance and suggestions for the use of recycled scrap tires by engineers interested in incorporating scrap tire-derived materials in construction projects.

For the use of recycled materials to become widespread in engineering construction projects, the materials must perform properly and regulating agencies must accept the use of these materials. Since 1991, MES and MDE have collaborated on scrap tire cleanups and demonstration projects to reuse scrap tires.

This Manual presents technical considerations and examples of uses of available materials derived from recycled scrap tires. The objective is to provide general engineering characteristics of assorted scrap tire materials and to discuss the pros and cons of replacing or supplementing traditional building materials with recycled scrap tire products. The Manual includes specific case studies of projects using scrap tire materials and a discussion of environmental and engineering performance of the materials.

The Manual is intended as conceptual guidance only. It is intended as an informational resource and any suggestions should be considered in consultation with individual design engineering appropriate for the scope of the particular project where use of these materials is proposed.[i]

The State of Maryland supports the recycling of scrap tires and encourages their re-use in the marketplace. For information on the scrap tire cleanup and recycling activities in Maryland, see MDE's annual scrap tire program reports at http://www.mde.state.md.us/ResearchCenter/Publications/index.asp. Questions concerning the recycling of scrap tires may be directed to MDE's Solid Waste Program at (410) 537-3318.

Sincerely,

James M. Harkins
James M. Harkins, Director
Maryland Environmental Service

Shari T. Wil
Shari T. Wilson, Secretary
Maryland Department of the Environment

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[i] Use of this Manual is at the discretion of the reader and the State of Maryland is not responsible for the results of any application of the materials discussed in this Manual.

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ABSTRACT

This Guidance Manual provides design engineers and the public with practical technical information related to the beneficial reuse of scrap tires. This Guidance Manual is an outcome of the 1991 Scrap Tire Recycling Act, adopted by the Maryland General Assembly and constitutes Maryland Environmental Service (MES) efforts to promote the reuse of scrap tires. The focus is on the use of tire derived aggregate (TDA) in civil engineering projects in Maryland.

This manual provides a review of Federal and Maryland regulations on scrap tires; presents key engineering TDA properties reported in the literature; and provides a discussion of the application of TDA in landfill, retaining wall, embankment, septic system, and other civil engineering projects. For each of these applications, general material requirements and performance considerations are discussed.

1. INTRODUCTION

1.1 Overview

Each year, over 270 million automobile and truck tires are removed from service and scrapped in the United States. According to the United States Environmental Protection Agency (USEPA), the need to manage scrap tires has given rise to numerous scrap-tire management programs and brought about laws or regulations in 49 of 50 states [USEPA, 1999]. Scrap tires have been beneficially utilized in many states. The percentage of scrap tires that were beneficially reused increased steadily from about 11% in 1991 to 87% in 2005, according to the Rubber Manufacturers Association (RMA) [RMA, 2006]. Examples of beneficial reuses of scrap tires in practice today include: (i) alternative fuel source for electric generation; (ii) fuel source for cement kiln operations; (iii) raw material for the production of industrial and consumer goods; and (iv) raw material for civil engineering construction.

The remainder of scrap tires are often disposed in various legal or illegal manners. One common disposal practice is to place scrap tires in large mono-fill stockpiles. These stockpiles provide the potential for creating undesirable and possibly hazardous conditions, such as increased mosquito breeding, rodent activity, and combustion. To avoid these conditions, it is desirable to reduce the quantity of stockpiled scrap tires through recycling and alternative-use programs. The RMA estimates that 188 million scrap tires remain in stockpiles in the United States, which represents a reduction of 81% since 1990, thanks to state efforts in developing sustainable scrap tire markets and enforcing laws and regulations for scrap tires.

In 1991, the Maryland General Assembly enacted the Scrap Tire Recycling Act to establish mechanisms for collection, transportation, recycling, and cleanup of scrap tire stockpiles in Maryland. With this Act, the Maryland Department of the Environment (MDE) was given the responsibility to regulate and enforce these activities, and to provide the public with information to properly manage scrap tires using approaches that are protective of the environment. With that objective in mind, this Guidance Manual (Manual) provides practical technical information for safely incorporating scrap tires into civil engineering projects in Maryland. The intended audiences are design engineers, other professionals, and the general public, interested in the reuse of scrap tires.

This Manual was prepared by Geosyntec Consultants of Columbia, Maryland, and was sponsored by MDE’s Scrap Tire Program, in coordination with the Maryland Environmental Service (MES).

1.2 Definitions

The American Society for Testing and Materials (ASTM) in ASTM D 6270, "*Standard Practice for Use of Scrap Tires in Civil Engineering Applications*", provides a comprehensive list of terms and definitions for scrap tires used in civil engineering applications [ASTM, 2008]. The following terms, as defined in ASTM D 6270, are used in this Manual.

- *Tire Chips* – pieces of scrap tires that are generally 0.05 to 2 inches (in.) in size and have most of the wire removed.
- *Tire Shreds* – pieces of scrap tires that are generally 2 to 12 in. in size.
- *Tire Derived Aggregate* (TDA) – any combination of tire chips and tire shreds used as an alternative to conventional mineral soil/aggregate in civil engineering applications.

The term TDA is used throughout this Manual to refer to a blend of shredded/chipped tires in various proportions.

1.3 Production of TDA

TDA is an engineered product made by cutting scrap tires into small pieces using specialized equipment, which includes shredders and shearing equipment. TDA is a more suitable material for reuse as aggregate when it is produced by a shearing process, in which cleanly-cut edges of the tire particles are obtained. Typically, shredders with sharp knives are used to obtain cleanly-cut edges. Screening is sometimes necessary to remove excess dirt and undesired small rubber particles. Magnetic separation is occasionally used to remove unwanted portions of metal fragments. Foreign objects, such as wood, must be removed by hand separation. A licensing system has been established in Maryland for managing, storing, collecting, transferring, recycling, and processing scrap tires. Selected regulations for scrap tires are presented in Section 2.

1.4 Overview of Applications of Scrap Tires

Throughout the last three decades, whole, chipped, and shredded scrap tires have been incorporated into a wide range of innovative applications. Examples of these applications include the use of:

- Whole Tires:
  - as tire bales for highway embankments; and
  - used with tires that have one sidewall removed for retaining wall construction;

- Processed Tires:
    - as granulated rubber incorporated to asphalt binder for asphalt pavement; and
    - as raw material for playground cover;
- TDA:
    - as thermal insulation to reduce frost penetration under highways;
    - as an alternative to soil/aggregate materials in civil engineering applications such as: (i) drainage systems for landfills and septic systems; and (ii) lightweight fill material for embankment or retaining wall construction; and
    - as an attenuator for ground vibrations in light rail applications.

Some of these applications of TDA are presented in Sections 5 through 7 of this Manual.

The use of TDA in construction can be cost-effective. If TDA is available locally, it could be more cost-effective than traditional fill materials. For example, the cost of using TDA was about 10 to 90% less in some projects compared to using gravel. In general, the largest cost of using TDA is associated with labor and equipment to shred the tires. At equal distances, transportation cost is expected to be less than the cost of gravel because TDA is two to three times lighter than conventional mineral aggregate. Typical reported unit costs for TDA and alternative materials are summarized below.

Material	**Unit Cost ($/yd^3 in-place 2007)**
TDA	\$27 to \$40
Expanded Polystyrene (EPS) Geofoam®	\$50 to \$70
Common Borrow	\$ 8 to \$16
Lightweight Aggregate	\$40 to \$60

Regardless of the ranges presented above, costs should be evaluated on a project-specific basis because local availability will significantly influence unit costs of scrap tires.

1.5 Guidance Manual Scope

The purpose of this Manual is to present design guidance for the use of TDA as an alternative material to soil/aggregate for civil engineering applications. For completeness, the other applications using scrap tires listed in Section 1.4 are briefly discussed in this Manual.

For each application, this Manual provides: (i) an overview; (ii) a discussion of environmental concerns; (iii) typical values of TDA engineering properties for design; (iv) a brief discussion of design methods; and (v) a discussion of selected case histories, when available. A list of cited references is also provided.

The remainder of this Manual is organized into seven sections. Section titles and brief descriptions of the remaining sections are presented below.

- *Section 2: Scrap Tire Regulations*, presents a summary of the State of Maryland and Federal requirements related to the handling, use, and disposal of scrap tires. MDE design submittal and review procedures are also presented.

- *Section 3*: *Engineering Properties of Tire Derived Aggregate*, presents an overview of typical TDA engineering properties, including material gradation, unit weight, shear strength, deformation, compressibility, and hydraulic conductivity.

- *Section 4: General Performance Considerations*, addresses major aspects and design considerations associated with the performance of TDA in civil engineering projects.

- *Section 5: Landfill Applications of Tire Derived Aggregate*, provides guidance on the use of TDA as an alternative material for the construction of landfill structures, including gas transmission layers, leachate drainage layers, cover drainage layers, and protective layers.

- *Section 6: General Civil Engineering Applications of Tire Derived Aggregate*, provides guidance for the use of TDA as lightweight fill for embankments, retaining walls, and septic fields.

- *Section 7: Other Applications of Tire Derived Aggregate*, presents a brief overview of other applications for TDA and ground rubber, including production of consumer and industrial products.

- *Section 8: References*, provides the references used in this Manual.

2. SCRAP TIRE REGULATIONS

2.1 Introduction

Regulations for handling, use, disposal, and recycling of scrap tires are a state-specific responsibility and regulations and administrative procedures vary from state to state. Although the Federal government does not specifically regulate scrap tires, some Federal regulations apply to them. Brief descriptions of Federal and Maryland regulations are provided in Sections 2.2 and 2.3, respectively.

2.2 Federal Regulations

Scrap tires are classified under Federal regulations as non-hazardous waste. However, because the combustion of tires can release hazardous compounds, such as volatile gases, heavy metals, and oil, emergency response actions for containment or cleanup of hazardous compounds may be administered under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as "Superfund". Such an emergency response occurred in 1983, in Winchester, Virginia, where a tire pile containing approximately seven million tires ignited, causing a smoke plume several thousand feet high, and releasing liquid oil and tar at a rate of 30 gallons per minute.

The USEPA Office of Solid Waste and Emergency Response (OSWER) prepared a comprehensive review of scrap tire programs for each state. The document entitled, "*State Scrap Tire Programs: A Quick Reference Guide*" [USEPA, 1999], presents a summary of contacts, governing legislation, program funding sources, handing regulations, and disposal restrictions for each state program. OSWER maintains a website (www.epa.gov/epaoswer/non-hw/muncpl/tires/index.htm) that contains a variety of information pertaining to scrap tire laws, markets, research, publications, alternative uses, and related industry links.

2.3 Maryland Regulations

2.3.1 Introduction

In Maryland, the law for establishing a scrap tire program is the Scrap Tire Recycling Act of 1991 [H.B. 1202]. Based on this Act, the Code of Maryland Regulations (COMAR) 26.04.08 was established to regulate storage, collection, transferring, recycling, and processing of scrap tires in Maryland. The Scrap Tire Recycling Act designates implementation of the Scrap Tire Program to MDE, MES, and the Maryland Comptroller of the Treasury. Descriptions of the specific responsibilities of each agency are available at the Scrap Tire Program home page [State of Maryland, 2007]:

http://www.mde.state.md.us/Programs/LandPrograms/Solid_Waste/ScrapTire/index.asp.

2.3.2 General Regulations

Scrap tire, if not disposed properly, will pose a fire hazard and provide a breeding ground for mosquitoes and other disease vectors. In 1991, the Maryland General Assembly adopted the Scrap Tire Recycling Act [H.B. 1202], which established a mechanism for the cleanup of scrap tire stockpiles and for the collection, transportation, and recycling or processing of the more than 5.6 million scrap tires that were then generated annually in Maryland.

Maryland regulations prohibit open dumping of scrap tires. Maryland Scrap Tire Management Regulations (COMAR 26.04.08) explicitly prohibit the disposal of tires in municipal solid waste landfills, unless MDE determines that the scrap tire recycling system does not exist or has insufficient capacity to accommodate the scrap tire generated. This ban includes all recycled tires (whole or shredded) that are removed from beneficial reuse applications such as those described in this Manual. Therefore, alternative disposal means must be found for this material.

The Scrap Tire Recycling Act also provides technical and operational standards for the storage of scrap tires with emphasis on fire hazard control. This Act requires that scrap tires, stored indoors or outdoors, comply with specifications contained in the National Fire Protection Association (NFPA) "*Standard for Storage of Rubber Tires (NFPA 231D)*" [NFPA, 1998] and with other applicable state or local fire and zoning regulations.

2.3.3 Maryland Scrap Tire Licensing

A licensing system has been established in Maryland to manage storing, collecting, transferring, recycling, and processing of scrap tires. The licensing system, which is administered by MDE, employs a series of permits to track and manage parties engaged in the scrap tire business. Specific permits issued by MDE [MDE, 2004b] include:

- **Scrap Tire Collection Facility Licenses.** There are licenses required for operators that collect or accumulate scrap tires temporarily on a site and then transfer them to licensed or approved scrap tire facilities. Three categories of licenses for collection facilities are described below.
    - *General License*: Facilities having not more than 50 scrap tires accumulated at a site at any given time.
    - *Secondary License*: Facilities having not more than 1,500 scrap tires accumulated at a site at any given time.
    - *Primary License*: Facilities having 1,500 or more scrap tires accumulated at a site at any given time.

- **Scrap Tire Recycler License.** Required for activities to convert scrap tires into a marketable product.

- **Scrap Tire Hauler License.** Required for a person that, as a part of a commercial business, transports scrap tires in Maryland to or from a licensed scrap tire facility.

- **Substitute Fuel/Tire Derived Fuel (TDF) Facility Approval.** Required for companies that use scrap tires (whole or chips) as a fuel or supplemental fuel.

- **Solid Waste Acceptance Facility Approval.** Required for a permitted refuse disposal system or facility that accepts scrap tires for collection or processing.

Field inspectors from MDE's Solid Waste Program monitor scrap tire operations for regulatory compliance. Legal actions are sought when non-compliance is observed and/or progress towards remediation of identified problems is ignored.

2.3.4 Maryland Scrap Tire Project Administration

MES has the authority to conceive and execute scrap tire cleanup projects, recycling projects, and alternative-use demonstration projects for public benefit in Maryland. Project proposals initiated by MES are presented to MDE for consideration and funding, which is obtained from the State Used Tire Cleanup and Recycling Fund. A summary of scrap tire projects undertaken each year is published in the *Maryland Scrap Tire Program Annual Report* submitted to the Senate Education, Health and Environmental Affairs Committee and to the House Environmental Matters Committee. Some previously funded projects are listed below.

- Cleanup of various tire stockpiles throughout the State.

- Use of recycled tires for surface safety at public school playground projects.

- Preparation of a Guidance Manual for Engineering Uses of Scrap Tires.

- Preparation of informational posters and television advertisements.

- Demonstration projects for TDA use in landfills:
  - as landfill liner protective layer at the Reich's Ford Landfill (Frederick County);
  - as drainage layer at the Westport Landfill (Allegany County);
  - as drainage material in stormwater ditches at Westover Landfill (Somerset County); and

  - as drainage material in closure cap at Newland Park Landfill (Wicomico County), Round Glade Landfill (Garrett County), Nicholson Road Landfill (Kent County), and Garrett County Landfill (Garrett County).

- Use of commercially-produced rubber mats in horse stalls at the Maryland State Fair.

- Use of scrap tires as material for sound barriers at Interstate highways I-95 and I-195.

- Use of rubberized asphalt at Maryland’s eastern shore.

Technical review and approval by the MDE Scrap Tire Program is required for anyone undertaking projects such as those described in this Manual because of the potential environmental impacts associated with the use of scrap tires as an alternative construction material. To be considered for assistance from the State Used Tire Cleanup and Recycling Fund, projects must include a public benefit component.

With respect to technical review, MDE requires that submitted engineering plans are signed and sealed by a Professional Engineer registered in the State of Maryland. The design must be for a project in which recycled tires will be used as an engineered product. Inclusion of waste tires (whole or shredded) in the design without a clear engineering function is not allowed. In addition to engineering plans, MDE may require preparation of documents describing waste tire supply and handling procedures to ensure that State regulations are observed.

3. ENGINEERING PROPERTIES OF TDA

3.1 Introduction

3.1.1 Overview

This section presents ranges of the most significant engineering properties necessary for preliminary design of TDA in a variety of applications. Before considering the use of TDA for a project, design engineers must understand TDA engineering properties and how these relate to completed project performance.

Various private and public agencies have performed a variety of studies on TDA properties over the past few decades in the United States. Numerous publications derived from these studies were reviewed in preparing this Manual. The main results reported in those references that are relevant for this Manual are summarized in the next sections.

Engineering properties can be obtained from site-specific test results conducted on TDA samples or, if necessary, published values.

Because TDA particles are relatively large (i.e., on the order of 0.5 in. or more), TDA can be considered similar to coarse aggregate (e.g., coarse sand, gravel to crushed rock). A significant difference between mineral aggregates and TDA is that individual particles of TDA are much more deformable than those of sand, gravel, or rock. Another significant difference is that the unit weight of TDA is much lower than that of sand, gravel, or rock; therefore, TDA can be considered a lightweight aggregate. Included in this section are discussions on: (i) engineering properties affecting both the performance of coarse aggregate and/or TDA; and (ii) properties that are characteristic only of TDA.

In what follows, descriptions of the basic material properties of tire rubber are presented followed by descriptions of typical TDA engineering properties such as:

- particle size and gradation;
- water absorption capacity;
- unit weight;
- shear strength;
- long-term and short-term deformation and compressibility;
- thermal conductivity; and
- hydraulic conductivity.

3.1.2 Sampling and Testing

Prior to construction, it is recommended that samples of TDA that will be used for a project be obtained from identified sources and be tested for the most relevant properties applicable to the project. Alternatively, these properties may be provided and certified by the scrap tire supplier; however, this is rarely done. When samples are collected and tests conducted, the frequency of sample collection and testing will depend on the amount of material to be used and on the nature of the project.

The standard ASTM D 6270 [ASTM, 2008] was prepared to provide guidance for testing of material properties, assessment of leachate generation potential, and descriptions of typical construction practices. This ASTM document is the standard by which testing of some of the TDA properties listed above should be conducted. However, following ASTM D 6270 does not relieve design engineers from the responsibility of using sound judgment when considering the use of TDA, selecting applicable tests, and developing specifications for construction and environmental protection.

3.2 Use of Soil/TDA Mixtures

This manual will focus mainly on the use of TDA by itself. However, design engineers may consider using TDA in a soil/TDA mixture as fill material. Compared to TDA, a soil/TDA mixture has higher unit weight, lower compressibility, lower hydraulic conductivity, and lower combustion potential. Added soil increases the unit weight and lateral earth pressures acting against retaining structures. If the soil to be added contains a large fraction of fine-grained particles, the drainage capacity of the fill mixture will likely be reduced. In general, the potential benefits of using TDA as a lightweight, free-draining material may be lost as the soil-to-TDA ratio increases. Mixing of soil and TDA may lead to additional construction costs. The potential benefit of a soil/TDA mix is that the mixture will have a higher shear strength than that of soil. This can be advantageous for embankments, where it is desirable to provide steep sideslopes. If the use of soil/TDA is considered for a project, the design engineer should prepare samples at various soil-to-TDA ratios and conduct tests to establish optimal conditions for construction, economy, and performance.

3.3 Basic Material Properties of Tire Rubber

3.3.1 Introduction

Modern tires are composed of natural rubber and synthetic rubber elastomers derived from oil and gas, and metallic intrusions. Other polymers, metals, and additives are also used in the manufacturing process to enhance performance. Basic properties of tire rubber particles (i.e., specific gravity, elastic modulus, and Poisson's ratio) are summarized below. In general, these properties of the basic material more or less are preserved after the tires are shredded into aggregate.

3.3.2 Specific Gravity

Specific gravity, G_s, is the ratio of the density of the solid phase of a material to the density of water at normal conditions. The specific gravity of tire rubber ranges between 1.02 and 1.27, with higher values corresponding to tire rubber containing steel inclusions [Bressette, 1984; Humphrey et al., 1992; Humphrey and Manion, 1992; Ahmed, 1993]. This range corresponds to densities greater than that of water and significantly lower than that of mineral aggregates, which typically range from 2.6 to 2.8. TDA does not float when submerged in water, which is considered a major advantage over other lightweight fills (e.g., some expanded polystyrene [EPS] Geofoam®) in submerged or flooding applications. The specific gravity of steel-belted tires is generally higher than that of glass-belted tires. The specific gravity of TDA can be estimated using methods contained in ASTM C 127 [ASTM, 2008].

3.3.3 Elastic Modulus

Elastic modulus, E, is the coefficient of proportionality between the stress applied and the strain measured, for example, in a one-dimensional tensile test. Lower values of E are indicative of layer deformities. The elastic modulus for tire rubber ranges from 180 pounds per square inch (psi) to 750 psi [Beatty, 1981]. As a comparison, the elastic modulus of dense, drained sands can vary from 6×10^3 psi to 12×10^3 psi (e.g., Kulhawy and Mayne [1990]). The elastic modulus for gravel can be much larger. Therefore, under the same stress conditions, TDA will deform much more than soil.

3.3.4 Poisson's Ratio

Poisson's ratio, μ, is the ratio of transverse strain (i.e., contraction) to longitudinal strain (i.e., extension), as measured for example, in a one-dimension tensile test. The Poisson's ratio of tire rubber is 0.5 [Beatty, 1981], which means that this material would deform at a constant volume. As a comparison, the Poisson's ratio for mineral aggregate varies between 0.15 and 0.45 (e.g., Kulhawy and Mayne [1990]).

3.4 <u>Size and Particle Gradation</u>

The parameters related to particle size and gradation that are of engineering interest include maximum overall particle dimension, aspect ratio (i.e., ratio of particle length to width), distribution of particle sizes, and amount of exposed wire.

The distribution of particle size is represented by a gradation curve (e.g., Figure 3.1), which is obtained in general accordance with ASTM C 136, "*Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*" [ASTM, 2008]. Gradation curves are developed by relating: (i) the percentage of the weight of sample fraction retained in standard U.S. sieves; and (ii) the particle size associated to each standard sieve opening. This ASTM standard was originally developed for soils; therefore, some modifications to the procedures may be necessary. The necessary volume of TDA to conduct the test varies from 5 gallons, for TDA with a 3-in. maximum size, to 25 gallons, for TDA with a 12-in. maximum size. For typical TDA materials, the set of U.S. sieves to be used in the test includes the 3-in., 2-in., 1-in., and No. 4 (0.187-in.) sieves.

Figure 3.1 shows an example of particle-size distributions of TDA reported in the literature. For these curves, the maximum TDA particle size ranges from about 0.1 to 3 in. In general, TDA particles should be smaller than 12 in. because larger particles will be difficult to place and compact.

In general, the fines content (i.e., fraction by weight smaller than a No. 200 sieve [0.0029 in.]) of TDA is typically low. In applications where a high hydraulic conductivity is desired, the fines content should be limited to 5% or less. Table 3.1 indicates that, based on the ranges of the coefficient of uniformity, C_u, and the coefficient of curvature, C_v (see definitions in Table 3.1), TDA is generally poorly-graded, with one predominant particle size.

The particle-size distribution of TDA influences the internal heating and combustibility potential, which is discussed in detail in Section 4.6. Based on the guidance of ASTM D 6270, for fill layers up to 3-ft thick, the portion of TDA passing the No. 4 sieve should be limited to 5% (by weight). For fill layers 3- to 10-ft thick, the portion passing the No. 4 sieve must not exceed 1% (by weight).

Other important parameters related to particle dimensions include the percentage of sample comprising exposed metal wire and the percentage of sample with protruding wire longer than 2.5 in. The amount of exposed wire must be limited because the oxidation of large amounts of exposed wire may become a source of internal heat and possibly result in combustion. In addition, the exposed wire can be a hazard to personnel working with the shreds and can puncture tires of vehicles on the fill. The proportion of loose wire in TDA is typically small, less than 1% by weight. In general, protruding wires longer than 2.5 in. are rarely encountered if adequate shredding equipment is used. Sample specifications provided by Humphrey [2006b] require that the amount of loose wire (i.e., completely separated from the rubber) be less than 1% by weight and that metal wire protrude: (i) no more than 1 in. from the edge of TDA on 75% of TDA particles (by weight); and (ii) no more than 2 in. on 90% of the TDA particles. State design guidelines or specifications (e.g., Georgia, Kansas, South

Carolina, and Virginia) require that 90 to 95% of TDA particles have protruding wires shorter than 0.5 in. from the edge of TDA particles. Design engineers should include verifications of these parameters in their testing programs.

When evaluating project requirements for particle size and gradation, design engineers must be aware that the quality of the produced material is dependent on the shredding process and quality control measures employed during production. Smaller TDA particles correspond to a larger number of passes through a shredder. The quality of the shredding process may affect the TDA properties. For example, dull cutting blades tend to produce elongated chips that result in a higher surface of exposed wire [Phaneuf and Glander, 2003].

3.5 Water Absorption Capacity

Water absorption capacity is related to the amount of water that can be retained on the TDA particle surface after drainage is allowed. Water absorption capacity is the percentage of water retained to the dry weight of the sample. Water absorption capacity of TDA ranges from about 2 to 4% [Humphrey, 2006a]. This range is comparable to that of mineral aggregate, including clean, coarse sand and gravel. Water absorption capacity can be estimated by performing a test in accordance with ASTM C 127 standard "*Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate*" [ASTM, 2008].

3.6 Unit Weight

3.6.1 Introduction

The unit weight, γ, of compacted TDA with a typical 3-in. maximum size is about 40 pounds per cubic foot (pcf), prior to long-term compression under its own weight. This value is thereby much lower than the typical range of 100 to 130 pcf for mineral aggregate.

The unit weight of compacted TDA can be estimated in the laboratory or in the field using techniques similar to those used for soils. In the laboratory, the testing method used for estimating TDA unit weight is similar to the method used for soils (ASTM D 698, *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort* [ASTM, 2008]). Standard ASTM D 698 has limitations when used with TDA because TDA particles are much larger than typical soil particles, and TDA particles do not fit well in the standard soil sample mold. In addition, the level of compaction energy used for TDA does not need to be as high as for soils. To circumvent these limitations, the use of a larger mold is recommended to accommodate TDA particles, as suggested in ASTM D 6270. Circular molds for TDA have diameters of 10 to 12 in. and heights of up to 12.5 in. [Ahmed, 1993; Humphrey, et al., 1992; Humphrey and Manion, 1992; Edil and Bosscher, 1992; Tweedie et al., 1998a]. The in-situ unit weight of TDA is often difficult to measure.

3.6.2 Factors Affecting Unit Weight of TDA

Most factors affecting the unit weight of mineral aggregate also affect the unit weight of TDA. These factors include compaction methods, compaction conditions, compaction effort, and particle-size distribution. These factors are discussed below. The discussion is limited to TDA with a maximum size of 3-in.

Compaction Methods and Compaction Conditions

Various authors studied the effect of compaction methods and compaction conditions on TDA unit weight (e.g., Ahmed [1993], Benda [1995], Humphrey et al., [1992], Humphrey and Manion [1992], Edil and Bosscher [1992], and Tweedie et al., [1998a]). The compaction methods investigated can be classified into: (i) "no compaction to light compaction" (i.e., using vibratory methods in the laboratory); (ii) "laboratory compaction" (i.e., compaction using Standard Proctor, Modified Proctor in the laboratory); and (iii) "field compaction" (i.e., using lightweight, hand-operated field compaction equipment or vibratory tamping foot roller). Table 3.2 and Figure 3.2 summarize results in these three categories.

For "no compaction to light compaction", unit weights ranged from 21 to 31 pcf, with an average of 29 pcf. The samples compacted using vibration in accordance with ASTM D 4253, "*Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*" [ASTM, 2008], had a similar unit weight of uncompacted TDA, indicating that vibration without tamping was ineffective when compacting TDA.

For "laboratory compacted" TDA, unit weights ranged from 32 to 44 pcf, with an average of 39 pcf. Higher TDA unit weights (i.e., from 38 to 44 pcf) were obtained when compaction was performed using relatively large molds, 8-in. in diameter or more. For mold diameters of 4 or 6 in., TDA unit weights ranged from 32 to 37 pcf, which is unrealistically low. This trend illustrates the need to use large molds to obtain unit weights in the laboratory.

For "field compacted" TDA, unit weights ranged from 41 to 48 pcf, with an average of 44 pcf. These values correspond to field compacted TDA prior to being compressed by the weight of overlying structures in which case the unit weight will be higher.

The unit weight that can be achieved in the field not only depends on the compaction methods described above (i.e., vibratory or tamping) but also on the thickness of the lift to be compacted and the number of passes of the compaction equipment. The compaction practice recommended by the Federal Highway Administration (FHWA) Turner-Fairbank Highway Research Center is to spread a 2-ft thick (minimum) and 3-ft thick (maximum) lift and compact this layer using at least three passes of a tracked bulldozer. For larger chips or thicker layers of chips, as many as 15 passes of a bulldozer may be required to achieve good compaction. A typical control method is to ensure that no noticeable rutting of the TDA occurs during the last pass of the bulldozer before the next lift is placed [USDOT, 2002].

Compaction Effort

Humphrey et al. [1992a] observed that beyond a certain level of compaction, increases in compaction effort had a marginal to no increase in TDA unit weight for constant gradation, moisture content, and compaction equipment. In that study, an eight-fold compaction energy increase, from 60% of standard Proctor test (i.e., 60% of 12,400 ft-lb/ft^3 according to ASTM D 698 [ASTM, 2008]) to the modified Proctor test (i.e., 56,000 ft-lb/ft^3 ASTM D 1557 [ASTM, 2008]), rendered an increase of only 5% in the TDA unit weight. These results suggest that only a modest compaction effort is required to compact TDA. Ahmed [1993] obtained similar trends. In general, it is sufficient to use 60% of the standard Proctor compaction energy for most applications. This effect results in significant savings in compaction costs when compared with the costs of compacting soil.

Moisture Content

Humphrey et al. [1992] observed that because TDA can retain only a small amount of moisture (2 to 4%, as presented in the previous subsection), the compaction of "wet" or "dry" TDA samples showed negligible variation in compacted unit weight.

In addition to the factors discussed above, due to the high compressibility of TDA (discussed in a subsequent subsection), its unit weight can increase significantly over time upon loading and compression.

3.6.3 Recommended Values of TDA Unit Weight

For compacted TDA with a size of 0.5 to 3 in., and prior to being compressed by overlying weight, an in-place unit weight of γ = 40 to 45 lbs/ft^3 can be assumed as the initial material unit weight for design. The unit weight of TDA after being compressed by overlying weight can be estimated using the magnitude of overlying weight and compressibility of TDA, as discussed in Section 3.8.

3.7 Void Ratio

The void ratio of TDA, e, can be estimated using the following relationship:

$$e = \frac{G_s \gamma_w}{\gamma_d} - 1 \qquad \text{(Equation 1)}$$

where: G_s is the specific gravity, γ_d is the dry unit weight of TDA, and γ_w is the unit weight of water. For practical purposes, the dry unit weight of TDA can be assumed equal to the compacted unit weight, γ. Values for G_s and γ can be used as presented previously. For other conditions, typical values can be obtained from Humphrey et al. [1992]. Using values of G_s and γ presented previously, typical values of void ratios range from 1.5 to 2.5 for uncompacted TDA, and 0.9 to 1.2 for compacted TDA. Typical values of porosity (n), which is defined as $n = e/(1 + e)$, range from approximately 0.60 to 0.70 for uncompacted TDA and from 0.45 to 0.55 for compacted TDA.

3.8 Compressibility

3.8.1 Introduction

Research results of short-term and long-term compressibility of TDA is summarized in this section. Typical values of TDA compressibility properties obtained from previous research can be used to estimate TDA deformation for preliminary design.

A significant difference between TDA and mineral aggregates is that individual particles of TDA are more deformable and tend to bend more easily than sand and gravel particles. TDA can undergo significant deformation under applied loads as the result of two mechanisms: (i) bending and rearrangement of particles; and (ii) compression of individual particles. Bending and particle rearrangement can occur during compaction or initial loading and results in permanent deformation. On the other hand, compression of individual particles is mostly recoverable. The deformation of TDA particles is also time-dependent and thereby additional deformation of TDA may occur under long-term load conditions. This deformation is commonly referred to as creep.

Because significant deformation may occur in TDA due to loading, the design of structures with TDA should include: (i) an estimate of the expected deformation; and (ii) an evaluation of the influence of these deformations on structural and non-structural components built on and around the TDA fill.

3.8.2 Compressibility Testing

The compressibility of TDA is typically obtained in a constrained compression test. In this test, TDA particles are placed in a rigid, cylindrical mold, and then an increasing vertical stress is applied and the vertical strain or deformation is measured. If the mold is instrumented to measure lateral stresses, parameters such as the elastic modulus, *E*, the Poisson's ratio, μ, and the at-rest lateral earth coefficient can be obtained.

According to ASTM D 6270 [ASTM, 2008], the test mold used in compressibility tests of TDA should have a diameter several times greater than that of the largest particle tested (typically diameters vary from 6 to 12 in.), and the ratio of the specimen thickness to diameter should be greater than one.

Because friction between the sidewalls of the test mold and the TDA sample can significantly affect the accuracy of laboratory results, special attention is required to minimize or eliminate this potential source of error. Humphrey and Manion [1992] investigated the effect of sidewall friction during compressibility tests using strain gauges located along the height of the specimen. They observed that up to 40% of the applied normal force was transferred to the sidewalls. Similarly, Drescher et al. [1999] performed a series of compression tests on samples of various heights and evaluated the friction in each of them. Test results were used to extrapolate the stress-strain relationship for a sample of “zero” height, a hypothetical situation without side friction. To eliminate or reduce the effect of side friction, the sidewalls of the test molds should be lubricated [ASTM, 2008]. Tweedie and Humphrey et al. [1998] evaluated the effect of side friction by comparing settlements predicted using laboratory compression curves with field data obtained from an instrumented, full-scale TDA retaining wall. Predicted settlements exceeded field measurements by 31 to 54%, on average. They observed that when the net force is calculated as the surcharge load minus the frictional resistance force measured at the interface of the TDA and the adjoining retaining wall, the recalculated settlement predictions generally agreed with the measured predictions.

3.8.3 Short-Term Compressibility Parameters

A typical stress-strain (or compression) curve obtained from a constrained compression test is shown in Figure 3.3. As shown in the figure, the initial portion of the curve is very steep, which indicates high compressibility. The curve becomes flatter as stress increases. The large strain in the initial portion of the curve is likely caused by particle bending and rearrangement. As mentioned earlier, strain due to particle rearrangement is non-recoverable. Subsequent unloading/reloading curves are similar to the flatter portion of this curve, which is elastic and largely recoverable. Similar trends were observed in TDA constrained compression tests conducted by Manion and Humphrey, 1992; Humphrey et al., 1992;

Nickles, 1995; Drescher et al., 1999; and Bernal et al., 1996. The results are summarized in Figure 3.4. The laboratory test results used to generate Figure 3.4 are presented in Table A.1 (Appendix A).

The data shown in Figure 3.4 were replotted in Figure 3.5 with the horizontal axis (i.e., vertical stress) in a log-scale. Similar to cohesive soils, the void ratio of TDA varied approximately linearly with the logarithm of vertical stress, and can be represented by two straight lines, one for recompression and one for virgin compression, respectively. The compressibility of TDA can then be represented by a recompression index, C_r, and a compression index, C_c, defined as:

$$C_r = -\frac{e_1 - e_2}{\log(\frac{\sigma_1}{\sigma_2})} \qquad \text{for } \sigma_1, \sigma_2 \leq P_c \qquad \text{(Equation 2)}$$

$$C_c = -\frac{e_1 - e_2}{\log(\frac{\sigma_1}{\sigma_2})} \qquad \text{for } \sigma_1, \sigma_2 > P_c \qquad \text{(Equation 3)}$$

where: e_1 and e_2 are TDA void ratios corresponding to vertical stresses σ_1 and σ_2, respectively, and P_c is the vertical stress that separates the recompression portion and virgin compression portion of the e-log$P$ curve (similar to the definition of preconsolidation stress for clayey soils). Table 3.3 summarizes C_r, C_c, and P_c values obtained from the data in Figure 3.5, C_r varies between 0.03 and 0.11, and C_c ranges from 0.27 to 0.54. For compacted TDA prior to compression under overburden pressure, P_c typically ranges from 200 to 600 psf.

The flatter portion of the TDA compression curve can be used to evaluate elastic parameters E and μ using the following procedures:

1. Calculate the constrained modulus, D, as the slope of the stress-strain curve in a constrained compression test using the unloading-reloading portion of the curve (i.e., the recoverable deformation) as:

$$D = \frac{\Delta\sigma_y}{\Delta\varepsilon_y} \qquad \text{(Equation 4)}$$

$$\Delta\varepsilon_y = \frac{\Delta h}{h} \qquad \text{(Equation 5)}$$

where: $\Delta\sigma_y$ is the vertical stress increment applied to the sample, $\Delta\varepsilon_y$ is the calculated vertical strain increment, Δh is the measured change in sample height, and h is the initial sample height. If the lateral stress increment $\Delta\sigma_x$, is measured in the constrained compression test, the at-rest lateral earth pressure coefficient, K_o, can be obtained as:

$$K_o = \frac{\Delta\sigma_x}{\Delta\sigma_y} \qquad \text{(Equation 6)}$$

The variables used in Equations 4 through 6 are illustrated in Figure 3.6.

2. The Poisson's ratio is calculated using the following relationship:

$$\mu = \frac{K_o}{1+K_o} \qquad \text{(Equation 7)}$$

3. The elastic modulus of TDA, E, is calculated as [Humphrey et al., 1992]:

$$E = \frac{1+\mu}{1-\mu}(1-2\mu)\,D \qquad \text{(Equation 8)}$$

Under a high overburden stress, vertical strains tend to increase linearly with increasing vertical stress at a slope similar to that defined by E. Elastic parameters can be used to estimate deformations of TDA for vertical stresses greater than approximately 20 psi.

Parameters, E, μ, D, and K_o, obtained from the test results of Figure 3.4 are summarized in Table 3.4. The results shown are for TDA particle sizes ranging from 0.5 to 5 in. K_o values range from 0.26 to 0.47; in comparison, K_o of normally consolidated granular soils typically range from 0.35 to 0.50 [Holtz and Kovacs, 1981]. μ for TDA ranges between 0.20 and 0.30, whereas for granular soil μ ranges from 0.15 to 0.45 [Kulhawy and Mayne, 1990]. The elastic modulus of TDA ranged from 16 to 26 kips per square foot (ksf), which is 1 or 2 orders of magnitude lower than the elastic modulus of granular soil. Figure 3.7 shows the relationship of void ratios of 3-in. maximum particle size TDA and varying vertical stresses. As shown in this figure, the void ratio decreases significantly at high stresses.

3.8.4 Long-Term Compressibility Parameters

The discussion in Section 3.8.3 focuses on short-term compressibility. However, a portion of TDA deformation is time dependent. Long-term compressibility of TDA was investigated by several researchers. Humphrey et al. [1992] performed long-term constrained compression tests that lasted for 31 days and found that vertical strains and horizontal stresses tended to increase over time under constant vertical stress. Tweedie et al. [1998] monitored creep of a full-scale retaining wall backfilled with TDA for a period of approximately 200 days. The majority of the deformation occurred within 50 days after surcharge loading of the backfill. Drescher et al. [1999] performed a comprehensive laboratory investigation of creep deformation under constrained and unconstrained conditions for a period of approximately 21 months. Strain rates were largest at the beginning of the tests, then decreased and became insignificant. Deformation during the first 50 days after loading only accounted for approximately 60% of the ultimate deformation. After two years, creep became almost negligible. Strain in unconstrained conditions was observed to be approximately two times larger than that in constrained conditions.

Wartman et al. [2007] conducted one-dimensional constrained compression tests on TDA and TDA-soil mixtures for a period of up to approximately 100 days. The time-dependent deformation was characterized using the modified secondary compression index ($C_{\alpha\varepsilon}$), a parameter commonly used to define secondary compression of fine-grained soils. The modified secondary compression index in these tests ranged from 0.0010 (50% TDA and 50% sand mixture by volume) to 0.0074 (100% TDA). $C_{\alpha\varepsilon}$ appears to be independent of particle size and load level. $C_{\alpha\varepsilon}$ values were found to be similar to back-calculated values from several TDA field applications, including fill for: roadway embankments [Bosscher et al., 1993; Dickson et al., 2001], fill behind a bridge abutment [Humphrey et al., 2000], and backfilled behind a retaining wall [Tweedie et al., 1998]. The time-dependent deformation obtained from these case histories and laboratory testing is presented in Figure 3.8. After $C_{\alpha\varepsilon}$ is obtained, the time-dependent settlement at a given time after fill placement, (ΔH_t) can then be estimated as:

$$\Delta H_t = H_o C_{\alpha\varepsilon} \log \frac{t_2}{t_1} \qquad \text{(Equation 9)}$$

where: H_o = initial thickness of the TDA layer; t_1 = time when time-dependent compression begins (assumed to be one day by Wartman et al. [2007]), and t_2 = time at which the magnitude of time-dependent compression is estimated.

3.8.5 TDA Layer Compression Estimate

A procedure to estimate the compression of a TDA layer under a surcharge load is presented in this subsection. The following conditions are assumed in this procedure:

- After compaction of the TDA layer and before the construction of an overlying soil structure (e.g., embankment; soil layer covering TDA fill):
    - initial thickness = H_o;
    - initial vertical stress at midpoint of the TDA layer = σ_{vo};
    - initial TDA unit weight = γ_o; and
    - initial TDA void ratio = e_o.
- After construction of the overlying structure over the TDA layer:
    - TDA thickness after compression = H_1;
    - vertical stress at midpoint of the TDA layer = σ_{v1};
    - TDA unit weight = γ_1; and
    - TDA void ratio = e_1.
- After a surcharge is applied to the overlying structure (e.g., traffic load):
    - final TDA thickness after compression = H_2;
    - final vertical stress at midpoint of the TDA layer = σ_{v2};
    - TDA unit weight = γ_2; and
    - TDA void ratio = e_2.

The procedure presented herein focuses on the compression, ΔH, of the TDA layer due to surcharge applied to the overlying structure, where $\Delta H = H_1 - H_2$. The compression of the TDA layer due to an overlying soil structure ($\Delta H = H_o - H_1$) requires that the TDA layer be overbuilt so that it results in a post-compression thickness, as specified in the design. The magnitude of overbuild can be estimated using the design chart presented in Section 6.2.3.

After a surcharge is applied, the final vertical stress, σ_{v2}, can be calculated as:

$$\sigma_{v2} = \sigma_{v1} + \Delta\sigma_v \qquad \text{(Equation 10)}$$

where: $\Delta\sigma_v$ = increase in vertical stress due to the surcharge applied.

When calculating the vertical stresses σ_{v1} and σ_{v2}, the in-place unit weight of TDA, γ_1, used should account for the compression of the TDA layer under the weight of the overlying structure. The in-place unit weight can be estimated using:

$$\gamma_1 = \frac{\gamma_o}{(1-\varepsilon_{v1})} \qquad \text{(Equation 11)}$$

where: ε_{v1} is the vertical strain of the TDA layer after the weight of the overlying structure is applied. Typical values of the initial unit weight, γ_o, can be assumed to be 40 to 45 lbs/ft^3. For simplicity, the following TDA in-place unit weights can be used.

Overburden pressure (psf)	0 to 120	120 to 1,000	1,000 to 2,000	2,000 to 7,000
In-place unit weight (pcf)	40 to 50	50 to 60	55 to 65	60 to 70

The compression of the TDA layer due to the applied surcharge ($\Delta H = H_1 - H_2$) can be estimated using the following equation:

$$\Delta H = \Delta H_s + \Delta H_t \qquad \text{(Equation 12)}$$

where: ΔH_s = instant compression of the TDA layer due to the applied surcharge and ΔH_t = time-dependent settlement.

The magnitude of ΔH_s can be estimated: (i) from a TDA compression curve obtained in the laboratory for conditions that are representative of those expected in the field; or (ii) using the simplified formulation that incorporates the compression and recompression indices, C_c and C_r.

If TDA compression curves are available from laboratory tests, the instant compression as a result of the surcharge will be:

$$\Delta H_s = H_o\,(\varepsilon_{v2} - \varepsilon_{v1}) \qquad \text{(Equation 13)}$$

where: ε_{v1} and ε_{v2} are the vertical strains corresponding to the overburden stresses σ_{v1} and σ_{v2} obtained from the TDA compression curves.

Alternatively, ΔH_s can be calculated using the following equations, depending on the magnitude of the initial and final pressures with respect to P_c, where P_c is the vertical stress that separates the recompression and virgin compression portions of the compression curve (see Section 3.8.3):

$$\Delta H_s = C_r \frac{H_o}{1+e_o} \log \frac{\sigma_{v2}}{\sigma_{v1}}\ , \qquad \text{if } \sigma_{v1} \text{ and } \sigma_{v2} < P_c \qquad \text{(Equation 14a)}$$

$$\Delta H_s = C_r \frac{H_o}{1+e_o} \log \frac{P_c}{\sigma_{v1}} + C_c \frac{H_o}{1+e_o} \log \frac{\sigma_{v2}}{P_c}, \qquad \text{if } \sigma_{v1} < P_c \text{ and } \sigma_{v2} \geq P_c \qquad \text{(Equation 14b)}$$

$$\Delta H_s = C_c \frac{H_o}{1+e_o} \log \frac{\sigma_{v2}}{\sigma_{v1}}\ , \qquad \text{if } \sigma_{v1} \text{ and } \sigma_{v2} > P_c \qquad \text{(Equation 14c)}$$

Typical values for C_c, C_r, and P_c are discussed in Section 3.8.3. The design engineer must use the initial thickness, H_o, and void ratio, e_o, in Equations 14a,b,c, if the initial TDA layer thickness (H_o) is known. Alternatively, the design engineer must replace H_o and e_o with the post-compression TDA thickness, H_1, and void ratio, e_1, respectively, in Equations 14a,b,c, if the TDA layer thickness is known after the construction of an overlying soil structure has taken place. Layer thicknesses H_o and H_1 can be related using the following equation:

$$H_o = \frac{H_1}{(1-\varepsilon_{v1})} \qquad \text{(Equation 15)}$$

The time-dependent settlement, ΔH_t, is independent of the applied load and can be estimated using Equation 9 and the long-term compressibility parameters presented in Section 3.8.4.

3.9 Hydraulic Parameters

3.9.1 Introduction

In general, TDA has higher hydraulic conductivity than most granular soils; therefore, TDA has been widely used as a drainage material. The flow through a porous material (e.g., drainage layer) per unit time for low-flow velocities (i.e., laminar flow) can be estimated as:

$$Q = k\, i\, A \qquad \text{(Equation 16)}$$

where:

Q = volume of flow through porous material;
k = hydraulic conductivity;
i = hydraulic gradient; and
A = gross cross-section area of porous material.

Hydraulic conductivity of porous material depends primarily on the void ratio. In granular soils, changes in overburden pressures do not significantly affect hydraulic conductivity. For TDA however, hydraulic conductivity is more sensitive to changes of overburden pressure because the void ratio of TDA can vary significantly with overburden pressure.

Transmissivity, θ, which is typically used to quantify the amount of fluid per unit of thickness that flows within a layer of porous material, is defined as:

$$\theta = k\,T \qquad \text{(Equation 17)}$$

where: T is the thickness of the porous media layer. Substituting Equation 17 into Equation 16, flow, Q, is expressed as:

$$Q = \theta\, i\, W \qquad \text{(Equation 18)}$$

where: W = width of water flow. In practice, flow is typically calculated per unit width (i.e., $W = 1$), which leads to:

$$q = \theta\, i \qquad \text{(Equation 19)}$$

where: q = flow per unit width.

3.9.2 Hydraulic Conductivity Tests

For TDA with particle sizes smaller than 0.75 in., the hydraulic conductivity can be estimated in accordance with ASTM D 2434 ("*Test Method for Permeability of Granular Soils Constant Head*" [ASTM, 2008]). However, TDA typically has particles greater than 0.75 in. To accommodate large TDA particle sizes, the hydraulic conductivity testing apparatus (i.e., permeameter) larger than that typically used for soil testing is needed. ASTM D 6270 states that: "*hydraulic conductivity of tire shred/soil mixtures should be measured with a constant head permeameter with a diameter several times greater than the maximum particle size*."

Testing of TDA hydraulic conductivity can be difficult because: (i) oversized testing molds (i.e., larger than 12 in. in diameter) are not common; (ii) a constant hydraulic head is difficult to maintain in highly-permeable TDA; and (iii) achieving field void ratio in the laboratory is not always possible. Specially-designed testing apparatuses may be needed to overcome such difficulties. Representative test setups can be found in the literature [Bressette, 1984; Humphrey et al., 1992].

Overburden pressure and hydraulic gradient used for hydraulic conductivity tests must be selected to represent field conditions. Because TDA is highly permeable, high flow velocities under high hydraulic gradient may lead to turbulent flow. Under such conditions, Equation 16 may not be applicable. To confirm that Equation 16 is applicable (i.e., flow rates are proportional to gradients), multiple tests must be performed at different hydraulic gradients. If a constant hydraulic conductivity is obtained for all gradients, then the flow is laminar and Equation 16 is valid. Otherwise, the hydraulic conductivity will be dependent on hydraulic gradient.

3.9.3 Analysis of Results

Figure 3.9 presents test results of hydraulic conductivity reported in the literature [Bressette, 1984; Hall, 1991; Lawrence et al., 1998; Humphrey et al., 1992; Ahmed, 1993; Geosyntec, 1997, 2002; Chu, 1998; Narejo and Shettima, 1995; and Reddey and Saichek, 1998]. Comparing hydraulic properties reported in the literature is difficult due to the large number of variables associated with hydraulic conductivity tests and different testing setups and procedures followed by different researchers. In Figure 3.9, data are shown as a function of the normal pressure applied during testing. Results correspond to TDA less than 3 in. in size. Hydraulic conductivity ranges from 0.01 to 59.3 cm/sec, having a median of 4.5 cm/sec. All data (104 points) are presented in Table A.2 (Appendix A). In comparison, the typical hydraulic conductivity of sand is 1×10^{-2} to 1×10^{-3} cm/sec [Lambe and Whitman, 1969].

In Figure 3.9, test results have significant scatter. This trend is largely influenced by the initial void ratio at the time of testing. In Figure 3.10, 31 data points of hydraulic conductivity were plotted as a function of void ratio for test results reported by Lawrence et al. [1998], and Humphrey et al. [1992]. The upper bound, lower bound, and average hydraulic conductivity are expressed in cm/sec in the following equations, which can be used to estimate the hydraulic conductivity when the void ratio is known.

Upper bound:

$$k = 222\, e^{4.6} \qquad \text{for} \sim 0.3 < e < 0.50 \qquad \text{(Equation 20)}$$

$$k = 39\, e^{2.1} \qquad \text{for } 0.50 < e < 1 \qquad \text{(Equation 21)}$$

Lower bound:

$$k = 9\, e^{2.0} \qquad \text{(Equation 22)}$$

Average:

$$k = 20\, e^{2.2} \qquad \text{(Equation 23)}$$

As mentioned above, hydraulic conductivity or transmissivity is affected by overburden pressure because of the high compressibility of TDA. Figure 3.11 [Geosyntec, 1997] presents an example of variation in TDA transmissivity for hydraulic gradients between 0.08 and 0.5 and confining pressures between 1,440 and 7,200 psf. As shown in this figure, transmissivity increases with decreasing gradient and decreasing normal pressure.

3.10 Thermal Conductivity

The thermal conductivity of TDA is 2 to 3 times lower than that of typical soil, making it an appealing solution for limiting frost penetration in the ground. The thermal conductivity of TDA is influenced by many factors. For example, thermal conductivity increases with particle size (as more air circulates in the voids) and the degree of compaction. Frozen TDA has higher thermal conductivity than thawed TDA and higher water content leads to higher thermal conductivity.

Several methods can be used to measure thermal conductivity. For TDA smaller than 1 in., a commercially available, guarded hot-plate apparatus can be used to measure the thermal conductivity of TDA. For TDA larger than 1 in., a large-scale hot-plate apparatus can be used [Humphrey et al., 1997a]. The thermal conductivity of TDA can also be back-calculated from field measurements [Humphrey et al., 1997a].

Shao et al. [1995] measured the thermal conductivity of TDA with maximum particle sizes ranging from 0.04 to 1 in. The thermal conductivities ranged from 0.0563 BTU/hr-ft-°F (0.0838 Cal/m-hr-°C) for very small (i.e., 0.04-in.) particles tested in a thawed state with water content less than 1% and low compaction, to 0.0988 BTU/hr-ft-°F (0.147 Cal/m-hr-°C) for 1-in. tire shreds tested in a frozen state with a water content of 5% and high compaction. Humphrey et al. [1997a] back-calculated the thermal conductivity of 2-in. TDA from field tests as 0.12 BTU/hr-ft-°F (0.18 Cal/m-hr-°C). For comparison, the thermal conductivity of typical soils is approximately 1 BTU/hr-ft-°F.

3.11 Shear Strength

3.11.1 Introduction

The shear strength of TDA can be modeled with the Mohr-Coulomb failure criterion as used with other granular material as follows:

$$\tau_f = c + \sigma \tan\phi \qquad \text{(Equation 24)}$$

where: τ_f is the shear resistance at failure; σ is the normal stress acting on the plane where failure is caused; and ϕ and c are the internal friction angle and cohesion, respectively. The Mohr-Coulomb shear strength parameters (c and ϕ) can be obtained from direct shear tests and triaxial tests in the laboratory as described below.

3.11.2 Shear Strength Testing

Direct Shear Testing

Direct shear testing has been used by various researchers to estimate the friction angle of TDA. As with other TDA parameters, the size of the shear testing apparatus affects results.

Typical dimensions of a direct shear testing apparatus used for TDA are 12 in. × 12 in. in plan dimensions and 9 in. in total thickness [Humphrey et al., 1992; Bernal, 1996; Geosyntec 1997; Cosgrove, 1995]. Humphrey et al. [1992] investigated the effects of the size of the shear testing apparatus on shear strength by performing duplicate tests using 8 in. × 8 in. and 16 in. × 16 in. testing apparatuses. It was found that the limitations of the 8 in. × 8 in. testing apparatus prevented the completion of the tests as the strength was not fully mobilized. These trends were not obtained using 16 in. × 16 in. and 12 in. × 12 in. testing apparatus. Therefore, the minimum plan dimensions recommended for shear strength testing of TDA is 12 in. × 12 in. Direct shear tests of TDA should be conducted in accordance with ASTM D 3080, "*Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions*" [ASTM, 2008].

Triaxial Testing

Large-diameter triaxial apparatus are typically used for TDA testing because conventional triaxial devices (i.e., diameters of 2 to 2.5 in.) are too small for testing TDA samples with particle sizes greater than 1 in. or particles with protruding wires [ASTM, 2008]. Dimensions of triaxial apparatus used in previous research for testing TDA were: (i) 12.5 in. in height and 12 in. in diameter [Ahmed, 1993]; and (ii) 8 in. and 4 in. in diameter [Benda, 1995].

3.11.3 Analysis of Results

Direct Shear Testing

Figure 3.12 shows shear resistance test results obtained from a 12 in. × 12 in. direct shear testing apparatus mobilized at displacements of 0.5, 1.0, 1.5, and 2 in., (Geosyntec [1997, 2004], Bernal [1996], and Humphrey et al. [1992]). The maximum TDA particle size used in these tests was 3 in. A summary of the data is presented in Table A.4 (Appendix A). These results indicate that the mobilized internal friction angle increases with displacement. Shear strength envelopes at each displacement are an average of the results. The shear strength envelopes are somewhat nonlinear and the friction angle is greater at lower confining pressures. No strong correlations were observed between shear strength and TDA particle size or degree of compaction. A bilinear strength envelope that fits the data shown in Figure 3.12 is defined as:

$$\tau_f = \begin{Bmatrix} \sigma \tan\phi_1 & 0 \le \sigma \le 10 \text{ psi} \\ \sigma \tan\phi_2 + c_2 & 10 \text{ psi} < \sigma \end{Bmatrix} \qquad \text{(Equation 25)}$$

Parameters ϕ and c are summarized in Table 3.5 for TDA with a maximum particle size of 3 in.

Triaxial Compression Testing

Benda [1995] performed triaxial compression tests at confining pressures of 5, 6.5, and 8 psi. Ahmed [1993] performed triaxial compression tests at confining pressures ranging from approximately 4.5 to 45 psi. These triaxial tests were performed on TDA of 0.38 to 2 in. in size. Results of 13 triaxial compression tests performed by Ahmed [1993] for axial compression strains ranging from 5 to 20% are presented in Figure 3.13a. Figure 3.13b shows results of 15 triaxial compression tests performed by Benda [1995] for strains ranging from 5 to 15%. Benda [1995] tested five TDAs with varying particle sizes and shapes. As with direct shear tests, results of triaxial compression tests indicate that: (i) higher shear strengths are mobilized with increasing strain; (ii) a peak shear strength was not attained for most cases analyzed; and (iii) a bilinear envelope appears to describe the shear strength of TDA. At each strain level, Equation 25 was fitted to the data reported by Ahmed [1993] and Benda [1995] and ϕ and c were calculated, as presented in Table 3.6. Shear strength values can be interpolated from this table for intermediate strain levels. The mobilized shear failure envelope is not significantly affected by: (i) particle size; (ii) particle distribution; or (iii) degree of compaction.

Triaxial Extension Test Results

Benda [1995] also performed 16 triaxial extension tests using the same five TDAs used for triaxial compression tests at relatively low confining pressures of 5, 6.5, and 8 psi. Unlike in triaxial compression and direct shear tests, a peak shear strength was achieved in triaxial extension tests. The peak friction angle varied from 45° to 61° and averaged 51° at a strain of about 20%. Comparatively, the friction angle in triaxial compression tests was 35° at 20% strain. Significantly larger strains would be required to achieve a peak strength in triaxial compression tests.

Effect of Wire on Shear Strength

The effect of wires on TDA shear strength has not been fully quantified although this parameter is considered to be a factor in causing high internal friction angles in TDA that can compare to those of dense gravels and sands [Marella, 2002; Tweedie, et al., 1998; Wu et al., 1997; Cosgrove, 1995; Humphrey and Sandford, 1993]. However, wires may eventually corrode with time; therefore, reliance on high friction angles as a result of wire inclusion should be considered with caution in long-term applications.

Recommended Shear Strength Parameters

TDA shear strength parameters can be estimated using Tables 3.5 and 3.6. TDA shear strength parameters are affected by the level of strain or displacement and, hence, these values should be selected for the expected conditions of strain (deformation) or displacement.

Shear strength of TDA is usually specified as a function of shear strain level. Humphrey et al. [1992] and Cosgrove [1995] defined the peak strength as the value that occurs when the horizontal displacement in a direct shear test (AASHTO Standard Test Procedure T 236, and ASTM D 3080 [ASTM, 2008]) reaches 10% of the testing apparatus length. Alternatively, project-specific information may be used to define failure. The anticipated allowable deformations should be used as guidance for the selection of the shear resistance. It is recommended to adopt strength parameters that correspond to the strains expected to occur in the field. Use a smaller friction angle value if shear deformation is a significant concern.

In applications where TDA shear strength provides a significant portion of the total resistance (e.g., enhancement applications where most of the potential slip surfaces go through the TDA fill), laboratory testing over a range of normal stresses appropriate for the project should be performed using project-specific test samples.

A list of specialty laboratories capable of performing large-scale direct shear tests on TDA is included in Appendix B.

4. PERFORMANCE CONSIDERATIONS

4.1 Overview

The following aspects should be addressed in civil engineering projects where TDA is used:

- puncture damage potential (when TDA is placed adjacent to geomembrane);
- stability;
- TDA compressibility;
- biochemical and physical clogging;
- internal heating and combustibility;
- environmental considerations; and
- constructability issues.

Each of these aspects is discussed in the next sections.

4.2 Puncture Damage Potential

The wires contained in TDA may create constructability and performance issues. For example, wires can puncture geomembrane liners if TDA is in contact with geomembrane. Two types of wire are commonly found in TDA [ASTM, 2008]: (i) bead wire consisting of high-tensile steel wire surrounded by rubber to form the bead of a tire and provide a firm contact with the rim; and (ii) belt wire consisting of brass-plated, high-tensile steel wire used in steel-belted tires.

Bead wire has more rigidity and higher tensile strength compared to belt wire. It is recommended that bead wire be completely removed from TDA when placed in direct contact with geomembranes to eliminate the geomembrane puncture potential. Belt wires are more flexible than bead wires and thereby can cause significantly less serious effects by direct contact with geomembranes [Geosyntec, 1998c and d]. Contact with belt wire may cause scratches and indentations, which may impair the ability of the geomembrane to serve as a primary hydraulic barrier.

If a geomembrane is placed adjacent to a TDA layer, a separation layer should be placed between the TDA and the geomembrane to provide protection against puncture. When TDA is underlain by a geomembrane (e.g., landfill cover drainage layer or landfill leachate collection layer), the main design consideration is geomembrane puncture resistance, which is largely dependent on the presence of wire in the TDA. Based on test pad results, Geosyntec [1998a and c] provide the following recommendations:

- TDA drainage layers can be placed directly on a 60-mil (1 mil = 1/1,000 in.) thick geomembrane provided that all the <u>bead</u> wire is removed, or a 6-in. thick soil cushion layer is placed to protect the geomembrane;
- TDA with <u>belt</u> wire can be placed directly on a 60-mil thick geomembrane and used as drainage material in landfill cell floor areas only;
- a non-woven geotextile [with a density of 12 ounces per square yard (oz/yd^2) or heavier] or a 6-in. thick soil layer should be used to reduce the potential for geomembrane damage from TDA <u>belt</u> wire to protect the geomembrane on sideslopes; and
- if TDA is free of wire, it may be placed directly over the geomembrane.

Phaneuf and Glander [2003] recommend a minimum thickness of 9 to 12 in. of soil to be placed between TDA and geomembrane. Donovan et al. [1996] suggest that direct contact between TDA and geomembrane may be acceptable based on the application of the criterion of higher hole-frequencies (i.e., defect or puncture) that admits a small but tolerable number of holes in the geomembrane as is commonly accepted in the evaluation of landfill cover systems using the program HELP (Hydrologic Evaluation of Landfill Performance) in evaluations and test pad demonstrations.

4.3 <u>Stability</u>

TDA must provide sufficient shear strength to resist against global stability failure in slopes and similar applications. In addition, the interface between TDA and other materials especially geosynthetics must have sufficient shear strength to resist potential sliding or pullout. These two issues are discussed in the following sections.

Slope Stability

Stability of TDA fill is an important design issue in applications such as embankments, retaining walls, or slopes. Similar to other particulate media, the stability of TDA is controlled mainly by unit weight and shear strength. TDA has lower unit weight and relatively lower shear strength than granular soil. The mobilized shear strength of TDA depends on the mobilized strain that the system is undergoing.

The assessment of the stability of TDA fills can be conducted using conventional stability methods developed for soils. The veneer stability of a thin layer of TDA on a slope can be assessed using analysis methods developed for infinite slope stability or sliding block-wedge analyses [Koerner, 1998; Giroud et al., 1995; Sharma and Lewis, 1994; Richardson et al., 2000]. These methods should consider pore pressures within the TDA layer due to seepage forces within drainage layers or gas pressures within landfill gas (LFG) transmission layers. For global slope stability, many commercial computer programs are available to analyze the slope stability. Shear strength parameters for TDA presented in Section 3.11 can be used in preliminary analysis.

Slope Stability Along Interface between TDA and Geosynthetics

In applications such as landfill covers, where TDA is placed over geosynthetics and the system is subject to down-drag, stability of the interface must be evaluated. TDA/geomembrane interface resistance is characterized by an interface friction angle (δ). The values of δ have been reported by Cosgrove [1995] for smooth and textured 60-mil high-density polyethylene (HDPE) geomembrane and TDA with particles up to 3-in. Direct shear tests were performed utilizing relatively large (i.e., 15 in. × 15 in.) testing apparatus to account for large TDA particles. For textured geomembranes, δ ranged from approximately 30° to 35°; for smooth geomembranes, δ ranged from approximately 15° to 21°. Bernal et al. [1997] also conducted direct shear tests and pullout tests to study the interaction between TDA and geosynthetics. The direct shear apparatus had plan dimensions of 11.8 in. × 11.8 in. and a total depth of 9 in. The interface friction angle between TDA and a flexible, polyester (PET), woven geotextile was 30° at a horizontal displacement of 1 in.

In applications such as retaining walls, where reinforcement is embedded in TDA fills, sufficient interface shear strength will be needed to resist pullout failure. For pullout resistance evaluation, a coefficient of interaction, C_i, can be used to estimate the average shear stress along the interface of the geosynthetics. This coefficient of interaction is defined as follows:

$$C_i = \frac{F_p}{2LW\,(\sigma_n \tan\phi + c)} \qquad \text{(Equation 26)}$$

where: F_p is the pullout force; L and W are the length and width, respectively, of the geosynthetic in contact with the TDA; σ_n is the applied normal stress; ϕ is the TDA internal friction angle; and c is the TDA cohesion. The coefficient of interaction obtained from pullout tests by Bernal et al. [1997] is summarized in Table 4.1. The pullout box is 47.2-in. long, 35.4-in. wide, and has a total depth of 20 in. The pullout force, F_p, was measured at a displacement of 2.5 in. The values of C_i obtained for TDA-geosynthetic are lower than those observed for sand over geosynthetic (typically between 0.9 and 1.1). C_i was also observed to be influenced by the aperture size of the geogrid. As the aperture size decreases, the coefficient of interaction increases. When designing a geosynthetics-reinforced earth structure with TDA as backfill, values listed in Table 4.1 can be used for a preliminary design and as a basis for estimating the pullout resistance of geosynthetics.

4.4 Compressibility

In some applications, such as highway embankments and bridge abutments, the compressibility of TDA may influence the serviceability of the project. To reduce settlement, a soil cover with sufficient thickness overlying the TDA fill can be used. A more detailed discussion on selecting the thickness of overlying soil cover is presented in Section 6.2.3. An alternate solution is to mix soil and TDA to reduce the compressibility of the backfill. However, adding soil to TDA may increase costs significantly in some projects. As more soil is added to the mix, the beneficial TDA properties as a lightweight aggregate are reduced.

Differential compression of TDA during construction and operation may affect the integrity of overlying structures and pavement. This must be taken into account during design by providing a soil bridging layer. In landfills, if a TDA layer supports a clay liner, cracks due to differential settlement may compromise the hydraulic barrier function of the clay liner. Geosyntec [1998b and d] recommends placing an 18-in. thick layer of soil over the TDA layer to provide a suitable foundation for the construction of compacted clay liners.

When TDA is used for drainage, the compression of TDA reduces the voids and thereby the hydraulic conductivity. The hydraulic conductivity may be further reduced due to biochemical or physical clogging (discussed below) in applications with high clogging potential (e.g., leachate collection layer). Caution should be taken when using TDA as a drainage layer in critical zones subjected to high overburden pressure.

4.5 Clogging

TDA is subjected to clogging as are other granular materials. Clogging decreases the drainage capacity of TDA, causing a buildup of pore water pressure. If the pore pressure buildup is in a slope, the higher pore pressure may lead to slope instability. In landfill applications such as leachate collection layers, clogging may cause buildup of hydraulic head on top of the liner system, which increases the leakage potential of landfill leachate. Clogging can be caused by biochemical or physical processes. The effects due to biochemical and physical clogging are discussed below.

Biochemical Clogging

In environments rich in microbes, a biological slime (biofilm) may develop on the surface of aggregate particles. Biological reactions may also cause inorganic constituents (e.g., calcium carbonate) to deposit, and this may further reduce the pore space. Rowe and McIsaac [2005] compared the clogging potential of TDA and gravel. They conducted column tests permeated with landfill leachate for up to two years. Leachate flowed through the columns at a rate of 1.3 ft per day. Under a compressive pressure of 3,132 psf, the hydraulic conductivity of TDA dropped from 0.7 to 2 cm/s to between 10^{-5} and 10^{-6} cm/s after one year. Gravel was observed to perform better than TDA. After two years, the hydraulic conductivity of gravel column was observed to be between 10^{-4} and 10^{-5} cm/s. Based on these test results, it is recommended that gravel be used in critical zones of leachate collection systems (e.g., landfill cell floor), which is subjected to high overburden pressure. TDA can be used in non-critical zones (e.g., landfill sideslope) with increased thickness to achieve a service life similar to that of gravel fill.

Physical Clogging

TDA has larger voids than most soils used for backfill. Physical clogging may occur as sediments build up over time within the voids of TDA fill. Adequate filtration and separation become fundamental design features that need to be considered in order to prevent build-up of sediments. When TDA fills are placed adjacent to a soil layer, an adequately designed geotextile [e.g., see Koerner, 1998] can provide the desired filtration and separation function to prevent clogging of the TDA layer.

4.6 Internal Heating and Combustibility Potential

Internal heating is a major concern for TDA fills and stockpiles. As metal wires of TDA oxidize due to corrosion and/or exothermic reactions, heat is generated. Under extreme conditions when the heat generation rate is faster than the dissipation rate, combustion of TDA can result if internal temperatures reach the auto-ignition point of approximately 550° to 650°F. Reported cases of fire due to TDA exothermic reaction include a road embankment in Ilwaco, Washington (January, 1996), a road embankment in Garfield County, Washington (January, 1996), and a retaining wall in Glenwood Canyon, Colorado (summer, 1995) [Humphrey et al., 1996b].

Research conducted to evaluate the triggering mechanisms of internal heating [Humphrey et al., 1996b] showed that the primary potential cause of TDA heat generation is oxidation of TDA exposed metal wires and rubber oxidation. Microbes may play a role in both reactions. Hence, the presence of large amounts of exposed wire directly contributes to increased oxidation rates. Humphrey [1996b] identified factors that facilitate this reaction, including temperature, leach water pH, nutrient sources (for microbial action), and the availability of oxygen and moisture. In addition, the relatively high insulation capacity of TDA, hinders dissipation of generated internal heat, and further increases the heating potential. Internal heating potential is also influenced by TDA particle size: smaller TDA particle sizes are generally more susceptible to combustion than larger TDA particles. Oxidation is more pronounced for small TDA particles because they have a larger cut-face surface area per unit mass.

ASTM D 6270 [ASTM, 2008] provides guidelines to minimize the internal heating potential of a TDA layer. These guidelines were subsequently modified by Humphrey [2001, 2006b] to take into account the gradations of TDA produced by a range of scrap tire processors. These guidelines recommend the TDA fill thickness must be limited to 10 ft to prevent heating problems. If TDA fill thicker than 10 ft is needed in design, the TDA fill can be broken into several thinner layers separated by soil layers. An example design of a TDA fill with thickness greater than 10 ft is presented in Section 6.3.4. TDA fill is divided into two classes in the modified guidelines: Class I Fill (i.e., TDA layers thinner than 3-ft); and Class II fills (a TDA layer 3-ft to 10-ft thick). The guidelines contain the following requirements:

- For Class I and II fills, TDA must be free of contaminants (including oil grease, gasoline, diesel, etc.) that can create a fire hazard. TDA that has been subjected to a fire are not permitted in a new fill because liquid petroleum products may have been released during the fire. For Class I and II fills, TDA must be free of fibrous organic matter, such as wood fragments and wood chips. TDA must 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 must protrude no more than 1 in. from the cut edge on 75% of the TDA particles by weight and no more than 2 in. on 90% of the TDA particles by weight.

- For Class I fills, TDA must have a maximum of 50% (by weight) passing the 1.5-in. sieve and a maximum of 5% (by weight) passing the No. 4 sieve.

- For Class II fills, TDA must have a maximum of 50% (by weight) passing the 3-in. sieve, a maximum of 25% (by weight) passing the 1.5-in. sieve, and a maximum of 1% (by weight) passing the No. 4 sieve.

No special design features are needed to minimize heating for Class I fills. For Class II fills, recommended design features include the following:

- Provide limited infiltration of air and water by covering the top and sides of a fill using a 20-in. thick layer of compacted soil of low permeability (e.g., clay). The topsoil layer must be sloped properly for drainage. In paved road embankments, pavement can be extended to the shoulder to reduce water infiltration.

- Isolate TDA layers from soils with high contents of organic matter (e.g., topsoil).

- If drainage layers are to be used at the toe of the TDA fill, well-graded granular soil (e.g., sand or gravel) should be used to limit free access of air. The drainage holes of walls should be covered using well-graded granular soil. The drainage layer thickness on the side of the fill should be the minimum necessary from the hydraulic viewpoint.

Phaneuf and Glander [2003] provide TDA storage guidelines for use in landfill construction projects. They recommended that TDA storage strategies ensure material integrity and minimize the risk of excessive internal heat generation and/or tire fires. TDA stockpiles must meet the following requirements: (i) stockpiles must not exceed a height of 20 ft; (ii) the base surface area of a stockpile should not exceed 10,000 ft^2 and the width should not exceed 50 ft; and (iii) the minimum separation distance between stockpiles must be 50 ft. For stockpiles greater than 10 to 12 ft in height, internal temperature monitoring plans may be implemented.

In Maryland, scrap tire storage regulations are based on guidelines developed by the National Fire Protection Association (NFPA), "*Standard for Storage of Rubber Tires (NFPA 231D)*" [NFPA, 1998]. An appropriate fire prevention plan must be submitted.

4.7 Environmental Considerations

The potential release of contaminants from TDA fills may pose an environmental risk to public health if not properly addressed. Potential environmental impacts of TDA are evaluated in this section.

Groundwater Quality

Humphrey and Swett [2006] provided a comprehensive literature review on the effects of TDA on groundwater quality. In field studies presented by Humphrey and Katz [2000 and 2001], TDA was placed either above or below the groundwater table, and groundwater quality was then evaluated. Results showed that the presence of TDA had a negligible effect on the concentration of metals such as arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), copper (Cu), and lead (Pb) relative to primary drinking water standards. However, concentrations of other metals related to secondary drinking water standards, such as iron (Fe) and manganese (Mn), were encountered at elevated levels. When TDA is placed below groundwater level, the manganese and iron released by TDA can be significantly above the secondary drinking water standard [Downs et al., 1997]. Because secondary standards are based on aesthetic factors (e.g., color, odor, and taste) and not on health concerns, the release of manganese and iron is not a critical concern. However, aesthetic concerns should be evaluated if TDA is to be placed below the groundwater table (ASTM D 6270 [ASTM, 2008]).

The leaching potential of organic compounds was also evaluated in these studies. The release of organics from TDA placed above the groundwater table was found to be below method-detection limits [Humphrey and Katz, 2000] and was not considered a significant concern. TDA placed below the groundwater table released a few organic compounds at low concentrations based on field results provided by Barris [1987]; Humphrey and Katz [2001]; and Twin City Testing [1990]. Results show that trace levels of a few volatile and semivolatile organics were found in water taken directly from TDA filled trenches. In these studies, the concentrations of water containments such as benzene, chloroethane, cis-1,2-dichloroethene, and aniline were above their respective preliminary remediation goals (PRG) for tap water when water is in direct contact with TDA. However, samples taken a few feet downgradient show that the effects are reduced to negligible levels. Humphrey and Swett [2006] concluded that TDA placed below the groundwater table have negligible effects for off-site water quality.

Based on the available information, it is concluded that the impacts of TDA on groundwater quality are small to negligible and that additional water quality monitoring is generally not needed. Nevertheless, the impact of TDA on the environment is site-specific and should be addressed on a case-by-case basis. For projects that present unusual environmental conditions, such as high or low pH, additional testing and monitoring should be conducted to systematically evaluate field performance.

Leachate Quality Considerations

In general, TDA is not classified as hazardous waste based on Toxicity Characteristics Leaching Procedure (TCLP) (USEPA Method 1311) regulatory limits [Zelibor, 1991; Ealding, 1992, ASTM D 6270 in ASTM, 2008; Tatlisoz et al., 1996; Liu et al., 1998]. However, the leachability of metals and organics from TDA may be influenced by the landfill leachate pH, which can vary from 3.7 to 8.5 depending on site-specific conditions [Sharma and Lewis, 1994]. Liu et al. [1998] reviewed various TDA laboratory leaching test programs and concluded that metals are more readily leached in acidic conditions and organics are more readily leached at basic conditions. As landfill leachate pH is typically close to neutral [Tchobanoglous et al., 1993], TDA will most likely not influence leachate quality.

Geosyntec [2002] performed site-specific leachate quality tests for a landfill protective layer at a landfill in Maryland. Based on 15 measured leachate parameters, it was concluded that the TDA did not have a negative impact on leachate quality because none of the concentrations exceeded the allowable influent concentration at the local wastewater treatment plant.

4.8 Constructability

The use of TDA fill may present some difficulties during construction. For example, when an overlying soil layer is to be constructed, the elastic compression and rebound of the TDA fill may make the soil layer difficult to compact. In landfill applications, a compacted clay liner directly above a TDA layer would not be feasible because the high compressibility of TDA may lead to cracks. This problem may be avoided if a soil-bridging layer is added between the clay liner and the TDA layer.

When a geomembrane is to be placed on top of TDA fill, the relatively large deformations induced by construction activities may impede the placement of the geomembrane or disrupt liner-seaming activities where a firm, stable foundation is required.

When construction equipment with rubber tires is considered for use over construction of TDA fill, potential for tire puncture due to exposed bead wire should be considered.

5. LANDFILL APPLICATIONS OF TDA

5.1 Introduction

Due to beneficial engineering properties such as high hydraulic conductivity, high internal friction angles (i.e., shear strength), and excellent heat insulation, TDA has become a viable alternative to many traditional landfill system components. The use of TDA in landfill containment systems has been permitted in several states (e.g., California, Florida, Maine, Mississippi, New York, Ohio, and Texas) under a diverse set of environmental conditions and regulatory environments. TDA can be used in the following landfill components:

- LFG collection layers;
- drainage layer in leachate collection systems;
- drainage layers in landfill covers;
- leachate flow trenches;
- landfill protective layers; and
- daily and intermediate covers.

An overview of these applications, gradation requirements, and primary design considerations is presented in this section.

5.2 Landfill Gas Collection Layers

5.2.1 Application Overview

The primary function of a LFG collection layer is to collect LFG under a landfill cover system and facilitate lateral transmission of the collected gas to an extraction system. LFG collection layers are typically located directly below a low-permeability layer (either a flexible membrane or compacted clay layer) in the cover system. LFG dissipation layers function according to the same principles of traditional systems, but are used in conjunction with passive venting systems or bioactive covers to dissipate LFG evenly through permeable cover soils and prevent the occurrence of emission ‘hot-spots’. Conventional materials utilized for these transmission layers are granular soils (sands and gravels) or geosynthetics (geonet and geocomposite). Compared to these materials, TDA can be very cost-effective in some projects.

5.2.2 General Material Requirements

TDA must satisfy the general requirement for fire control, as presented in Section 4.6, when used for LFG collection applications. Additionally, the maximum TDA particle size should be no greater than 12-in., and 95% of the particles should be less than 6 in. [ASTM, 2008] to achieve adequate thermal and hydraulic conductivities. Table 5.1 presents recommended TDA gradations [Geosyntec 1998b] for LFG collection systems.

5.2.3 Performance Considerations

When using TDA material for LFG collection systems, the primary performance goal is to ensure adequate gas transmissivity to prevent gas pressure buildup. Additionally, the LFG collection system should not damage impermeable layers such as the overlying landfill cover system. These considerations are addressed below.

Gas Transmissivity

Thiel [1998] and Richardson et al. [2000] provided a method to design LFG transmission layers utilizing gas transmissivity parameters based on permeability relationships. The overall approach is centered on estimating a potential LFG production rate for a given waste mass and then using this rate to design the gas transmission layer. Several drainage media can be selected to collect LFG, including TDA; however, TDA may exhibit some complications including clogging and compressibility. TDA clogging will decrease gas transmissivity. To prevent infiltration of surrounding soil, a geotextile separator should be installed. When selecting transmissivity values, the effect on transmissivity by overburden pressure must be considered. As overburden pressure increases, void ratio and the thickness of the gas collection layer decreases, and gas transmissivity decreases. The TDA compressibility can be estimated using data presented in Section 3.8. TDA compressibility is not of significant concern in cover systems, where overburden is low.

Integrity of Impermeable Layers

Protruding or loose bead wires can puncture geosynthetic layers (e.g., geomembrane or geosynthetic clay liner [GCL]). Belt wires can scratch geomembranes used in the overlying layer of final cover systems. A protective soil layer may be required between a TDA gas collection layer and GCL or geomembrane. Section 4.2 provides further recommendations on the use of TDA adjacent to geomembranes.

TDA layers may cause problems when placed under impermeable cap systems. When a compacted clay liner (CCL) cap system is to be placed, a separation soil layer may be required between the TDA layer and the CCL. A test pad constructed in California showed that a 1-ft thick clay layer compacted over TDA had numerous cracks [Humphrey, 2006]. A second 1-ft thick layer compacted over the first clay liner still had noticeable cracks. It was reported that an 18-in. thick soil layer over 6 in. of TDA, provided an adequate surface for construction of a CCL [Geosyntec, 1998a]. When a geomembrane is to be placed on top of TDA fill, potentially large deformations may make the placement of the geomembrane difficult or disrupt liner seaming activities where a firm stable foundation is required. A minimum of 12 in. of soil must be placed over the TDA to allow geomembrane placement and compaction of overlying soil layers [Geosyntec 1998b]. A geotextile may be used as a separator between the TDA and the soil. To place geomembrane directly on tire shreds, a field trial is needed to demonstrate that the geomembrane can be placed, seamed, and covered with soil without damaging the geomembrane.

5.3 Drainage Layers in Leachate Collection Systems

5.3.1 Application Overview

TDA can be used as a drainage material in leachate collection systems. A leachate collection layer provides drainage to remove from a landfill, liquids generated by and percolating through waste. These layers are typically located above the liner. Conventional materials used for leachate collection layers are granular soils, such as sands and gravels, or geosynthetics, such as geonet and geocomposite. In some projects, TDA may be a cost-effective alternative compared to these conventional materials. However, some evidence suggests that physical or biological clogging may occur after the material has been in the landfill environment for some months or years, so the use of TDA in noncritical areas of a cell such as side slopes may be preferred by the design engineer and regulators.

5.3.2 General Material Requirements

In addition to the general material requirements for fire control presented in Section 4.6, the maximum size of TDA particles used in a leachate collection system should be less than 12 in. [Geosyntec, 1998d]. The recommended requirement for TDA gradation is presented in Table 5.2 [Geosyntec, 1998d].

5.3.3 Performance Considerations

The primary performance considerations are to ensure enough drainage capacity to avoid the buildup of water pressure over the base liner. Because the leachate collection layer is placed at the bottom of the landfill, where it is subject to high overburden pressure, the high compressibility of TDA can lead to a significant reduction of void ratio and thereby drainage capacity. Additionally, TDA should not endanger the structural integrity of other liner system components placed next to it (e.g., geomembrane). These aspects are discussed below.

Compressibility and Void Ratio

Because TDA is highly compressible, it is necessary to provide extra thickness so that the minimum thickness requirement on the TDA layer can be met after it has been compressed under the applied overburden.

The permeability and clogging potential of TDA should be evaluated considering the void ratio of TDA after it is compressed under the applied overburden. As shown in Figure 3.7, the void ratio decreases significantly at high stresses, which leads to low permeability and high clogging potential, as discussed below.

Transmissivity

Most State regulations for landfill leachate drainage layers require a 12-in. thick sand layer with a hydraulic conductivity of 1×10^{-3} cm/s or greater. When TDA is used as a leachate drainage layer, the transmissivity of TDA is an important concern in design because of the void ratio decrease and the clogging potential.

As discussed in Section 4.4, TDA typically has a high compressibility. TDA compressibility should be taken into account along with hydraulic conductivity. As the leachate collection layer is located at the base of a landfill, the TDA layer will be subjected to relatively high overburden stresses, which may significantly reduce void ratio and subsequently, hydraulic conductivity. For typical landfill overburden pressures (10,000 to 12,000 psf), the thickness of TDA may be reduced by as much as 50% [Donovan et al., 1996; Nickels, 1995; Humphrey et al., 1993; Humphrey and Manion, 1992; Hall, 1991]. Donovan et al. [1996] reported that the minimum hydraulic conductivity for several TDA types were still greater than 0.1 cm/s under overburden pressures up to 12,000 psf.

As discussed in Section 4.5, TDA has a high potential for physical and biochemical clogging in landfill environments, which may reduce hydraulic conductivity. The laboratory simulation conducted by Rowe and McIsaac [2005] showed that under a compressive pressure of approximately 3,000 psf and a leachate flow rate of 1.3 ft^3/ft^2/day, the hydraulic conductivity of TDA dropped from 0.7 to 2 cm/s to 10^{-5} and 10^{-6} cm/s after one year. To prevent physical clogging, a geotextile separator should be used. Due to high potentials for clogging, it is preferable to use TDA drainage layer in non-critical zones, such as landfill sideslopes.

Structural Integrity

TDA should not be placed directly on a geomembrane liner because metal wire could puncture the liner under high overburden pressure. A minimum 12-in thick layer of granular soil should be placed between the TDA layer and the geomembrane as a protective layer. Section 4.2 provides a guideline to minimize the potential damage to geomembrane liners.

5.4 Landfill Cover Drainage Layers

5.4.1 Application Overview

The purpose of a drainage layer of a landfill cover is to prevent surface water infiltration into the landfill. Landfill cover drainage layers are typically located above the hydraulic barrier component of the cover system. Conventional materials used for landfill cover drainage layers are granular soils, such as sand and gravel, or geosynthetics, such as geonet and geocomposite. The use of TDA in landfill cover drainage layers is appealing because the potential problems associated with high compressibility and clogging potentials are minimal. At the cover, the overburden pressure is relatively low and the environment is relatively clean (less microbes), compared to a leachate collection layer. In some projects, TDA provides a more cost-effective solution than conventional granular soil or geosynthetic material.

5.4.2 General Material Requirements

The gradation requirement presented in Section 5.3.2 also applies to TDA used as a landfill cover drainage layer.

5.4.3 Performance Requirements

The transmissivity of the landfill cover drainage layer should be large enough to avoid ponding of water over the landfill cover. Compared to the case of a leachate drainage layer, the overburden stress applied to the landfill cover drainage layer is much smaller than the case of the leachate collection layer, because it only consists of the weight of the soil cover. Accordingly, the compression of this TDA layer is small. The potential of biochemical clogging is relatively low because the water collected through the cover drainage layer is usually cleaner than landfill leachate. Therefore, the long-term reduction in transmissivity is not as significant as in the case of a leachate collection layer. A geotextile separator should be used above the TDA layer to prevent clogging due to vegetative root penetration and/or infiltration of fines.

Because of the low overburden stress in this application, TDA can be placed directly over the geomembrane provided that the amount of exposed metal wires is minimized. In such cases, the slope stability for potential sliding along the geomembrane/TDA interface (i.e., “veneer” stability) should be considered (see Section 4.3). A textured geomembrane can be used to increase the interface shear resistance along slopes. Care should be taken to insure that there is sufficient protection for the geomembrane, and that stability of the design is adequately assessed.

5.5 Landfill Protective Layers

5.5.1 Application Overview

Protecting the liner system from protruding waste as the initial waste lift is placed on the constructed liner system is critical as protruding parts in the waste can puncture liner components such as GCLs, geomembranes, and compacted clay layers, or obstruct leachate collection pipes. Landfill protective layers provide a physical separation and protection buffer between the overlying waste and the underlying landfill containment system (e.g., leachate collection system and hydraulic barrier components). Typical protective layers are placed over the leachate collection layer with thicknesses that range from 12 to 24 in. Soil layers are conventional materials used for landfill protective layers. However, TDA can be a more cost-effective alternative compared to the soil protective layer in some projects.

5.5.2 General Material Requirements

General material requirements presented in Section 4.6 must be satisfied. Additionally, for landfill protective layers, the recommended maximum size of TDA particles Geosyntec, 1998d is 18 in. The gradation of TDA particles should also satisfy the requirements presented in Table 5.3.

5.5.3 Performance Consideration

The main function of the protective layer is to serve as a buffer between the overlying waste and underlying landfill liner. Because the liner system is typically under high overburden pressure, the TDA protective layer should be separated from the liner components (e.g., geomembrane or GCL) by a soil layer to avoid puncture damage. When the underlying leachate collection layer consists of geocomposite, a protective layer is still required. For this case, a combination of soil and TDA materials can be used as a protective layer.

5.6 Leachate Recirculation and Other Landfill Liquid Application Systems

5.6.1 Application Overview

The purpose of leachate recirculation is to reintroduce the collected leachate into the waste to accelerate its degradation. Important elements of leachate recirculation systems are leachate recirculation trenches, which are typically filled with granular soils. Because of the high hydraulic conductivity, TDA can be an appealing cost-effective solution for this application.

5.6.2 General Material Requirements

The requirement for TDA as a leachate recirculation material in leachate collection trenches is similar to that specified in Section 5.3.2.

5.6.3 Performance Considerations

The major concern associated with the use of TDA for leachate recirculation trenches is biochemical and physical clogging. A geotextile separator can be used to prevent physical clogging.

5.7 Daily and Intermediate Cover

Another landfill application of TDA is daily and intermediate cover, however, due to the large voids it contains, TDA by itself is not efficient in controlling disease vectors, odors, and limiting infiltration of water. Additionally, TDA has a high potential of flaming. Humphrey [2006a] recommended using a 50/50 mix of TDA and soil. The use of a 50/50 TDA/soil mixture for daily cover has been successful in landfills in South Dakota [Donovan, et al., 1996; Humphrey, 2006a] and Virginia [Humphrey, 2006a]. The Virginia Department of Environmental Quality (VDEQ) has approved the use of TDA/soil mixtures containing at least 50% of soil as landfill daily cover.

Although Maryland has not yet received any requests for this type of application, MDE will review proposals for technical merit if a landfill permittee requests the use of TDA for this purpose.

5.8 Case Studies

5.8.1 Newland Park Landfill [Geosyntec, 2002]

Project Overview

A scrap tire demonstration project was conducted at the Newland Park Landfill in Salisbury, Maryland. The site contains an inactive, unlined disposal area and a series of lined disposal cells that were constructed between July 1995 and January 2002. The scrap tire demonstration project was conducted within two of the lined cells. Each cell covers an area of approximately seven acres. A 2-ft thick layer of TDA was installed on top of the existing soil protective layer in one of the cells. The performance of this cell (referred to as the TDA cell herein) was monitored continuously for five years, and compared with the purpose of the other cell without a TDA layer (control cell). A typical cross section of the cell liner system and tire-chip layer is illustrated in Figure 5.1. The cross section consists of the following components, from top to bottom:

- a 2-ft (0.6-m) thick layer of TDA;
- a 2-ft (0.6-m) thick layer of protective cover sand designed to protect the liner system from puncture;
- a non-woven, needle-punched geotextile filter designed to prevent the protective cover soil from clogging the underlying geonet drainage layer;
- a HDPE geonet drainage layer that provides a pathway for leachate to flow rapidly to collection pipes, which in turn convey the leachate to sumps where the leachate is removed from the landfill; and
- a composite liner consisting of a 60-mil (0.06-in.) thick HDPE geomembrane underlain by a GCL.

Performance Evaluation

The monitored hydraulic head above and within the TDA layer increased temporarily with precipitation and dissipated rapidly after precipitation, thus indicating the high permeability nature of the TDA layer. After five years of operation, the TDA layer continued to provide free passage of leachate into the underlying leachate collection system. The maximum thickness of waste overlying the TDA layer was up to approximately 60 ft during the monitoring period. The temperature measured within the TDA layer was observed to be slightly lower than that of the waste, and well below the combustion limit. During the initial months after waste placement, the concentrations of iron, chromium, lead, zinc, selenium, and FOG (fat, oil, and grease) in leachate were greater in the TDA cell than in the control cell. However, these concentrations were observed to be similar for the TDA cell and the control cell 20 months after waste placement. None of the concentrations exceeded the allowable influent concentration.

5.8.2 DSI Superfund Landfill [Andrews and Guay, 1996]

Project Overview

TDA was used as a cover drainage layer in the DSI Superfund Landfill, located in Rockingham, Vermont, on the west bank of the Connecticut River. The original design required a 12-in thick sand layer as drainage layer, with 28,000 cubic yards in total volume. TDA was considered as an alternative to sand to reduce cost. Due to the limited stock of TDA near the site, TDA was used only on a portion of the landfill and sand on the remaining portion of the landfill, thus providing the opportunity to compare the performance of the two materials. The cross section consists of the following components, from top to bottom:

- 24-in. topsoil/vegetative support layer;
- geotextile filter;
- 12-in. sand or TDA drainage layer;
- 40-mil textured geomembrane primary barrier layer; and
- 24-in. soil secondary barrier layer.

Material Properties

The engineering properties of the TDA and sand used in this project are presented in Table 5.4.

As discussed in Section 3.11, the shear resistance of TDA depends on the displacement or strain level. The shear strength of TDA selected for this project was determined from a displacement of 1.2 in. using direct shear tests. A normal stress range of 180 psf to 600 psf (equivalent approximately to 1.5 to 5 ft of overlying soil) was selected for the tests.

Stability Analysis

The stability of the TDA layer on a 3H:1V (3 horizontal to 1 vertical) slope was analyzed. The slope stability factor of safety of the drainage layer with 1 in. of water at the bottom was calculated at 1.5 under non-seismic conditions and 1.4 under seismic conditions.

Puncture Damage Potential

Because TDA was placed directly above the geomembrane layer, the puncture damage potential was evaluated using test panels. Under normal stress of 600 psf (equivalent to approximately 5 ft of overlying soil), the overall appearance of the 60-mil very low-density polyethylene (VLDPE) geomembrane was not significantly changed although scratches and abrasions could be observed on the surface. Excavation during construction showed no puncture or ripping on the geomembrane.

Quality of Discharge Water

The construction of the cover was finished in November 1994. Water samples were obtained from the discharge of the cover drainage layer in October 1995 and May 1996. No volatile organic compounds (VOCs) were detected and only three semi-VOCs were detected in one sample just above the detection limit, and several metals were identified at concentration levels below the level of concern.

6. GENERAL CIVIL ENGINEERING APPLICATIONS OF TDA

6.1 Introduction

TDA has been used in a wide range of civil engineering projects. Typical applications include the use of TDA as lightweight fill material behind retaining walls and in highway embankments, and as coarse aggregate in septic leach systems. These applications and associated performance considerations are presented in this section.

6.2 Backfill Behind Retaining Walls

6.2.1 Application Overview

TDA has been used as lightweight fill for retaining walls to replace commonly used granular soil backfills. The use of TDA provides some advantages. First, the low unit weight of TDA helps to decrease the lateral earth pressures acting on the retaining wall, thus reducing the cost of the retaining wall. Second, for walls founded on weak soils, the low unit weight helps to increase global stability and to avoid failure due to insufficient bearing capacity. Additionally, TDA is a free-drainage material and provides good frost insulation.

6.2.2 General Material Requirements

For this application, TDA must satisfy the general material requirements specified in Section 4.6. Additionally, for retaining walls and embankment applications, the following gradation requirements (specifications for 'Type B' TDA in Humphrey [2006b]) can be used as guidance on the selection of TDA material as backfill material:

- a minimum of 90% (by weight) must have a maximum dimension, measured in any direction, of 12 in. and 100% must have a maximum dimension, measured in any direction, of 18 in.;
- a minimum of 75% (by weight) must pass the 8-in. sieve;
- a maximum of 50% (by weight) must pass the 3-in. sieve;
- a maximum of 25% (by weight) must pass the 1.5-in. sieve;
- a maximum of 1% (by weight) must pass the No. 4 sieve; and
- all TDA particles must have at least one sidewall severed from the tread.

6.2.3 Performance Consideration

Compressibility and Settlement

The compressibility of TDA may be a significant consideration in the design of retaining walls given that its elastic modulus is typically 1 to 2 orders of magnitude less than that of granular soils. TDA fill needs to be overbuilt to accommodate the anticipated compression. Humphrey [2002] developed a design chart for calculation of overbuild, which is reproduced as Figure 6.1. This design chart is developed for TDA fill with 12-in. maximum size. For smaller TDA fill, with 3-in. maximum particle size, increase the calculated overbuild by 30%.

For fill cross sections with one layer of TDA, the following procedure can be followed for the calculation of overbuild:

- calculate the vertical stress that will be applied at the top of the TDA fill; and
- find the amount of overbuild from Figure 6.1 using the calculated vertical stress and the desired final compressed thickness of TDA fill.

As discussed earlier, compression of TDA is also time-dependent. Humphrey [2006a] estimates that the long-term compression will be an additional one to 2% of the fill thickness. The secondary compression can also be estimated using the modified secondary compression index ($C_{\alpha\varepsilon}$) as discussed in Section 3.8.4. To minimize the effect of the time-dependent deformation, a 60-day waiting period may be needed before the construction of overlying settlement-sensitive structures takes place. For projects where the thickness of the fill can be tapered from full thickness to almost zero with a slope of 2H:1V to 4H:1V, a 30-day waiting period may be adequate [Humphrey, personal communication 2007].

To minimize the deflection on top of the fill in projects such as highways or bridge abutments, the use of an overlying soil cover with enough thickness to bridge significant surface deflection should be considered in design. Guidance for selecting soil cover thickness for highway projects is included in Section 6.3.3. For retaining walls used for other purposes, the required thicknesses of overlying soil cover can be assessed in terms of loading condition, TDA layer thickness, and function of the specific project. For example, greater soil cover thickness above the TDA layer should be used if: (i) relative settlement is critical for the project; (ii) a large surcharge will be applied on top of the fill; and (iii) TDA fill is relatively thick.

Lateral Earth Pressure

The low unit weight of TDA leads to significant reduction of lateral earth pressures when compared to walls with granular backfill. The lateral earth pressure of TDA on a wall can be estimated using the coefficient of lateral pressure. Under at-rest conditions, the coefficient of lateral earth pressure (K_o) is based on material properties (i.e., friction angle) or obtained from laboratory constrained compression tests [Humphrey et al., 1992] as presented in Section 3.8. Results obtained from field retaining walls [Tweedie et al., 1998a,b] indicate that the coefficient of lateral earth pressure of TDA varies with depth and level of surcharge. The ranges of K_o obtained from laboratory tests [Humphrey et al., 1992] and field tests [Tweedie, et, al., 1998a] are summarized in Table 6.1. Tweedie et al. [1998a] also studied the coefficient of active earth pressure (K_a), which takes place when the retaining wall is moving outward enough to mobilize the active state. Wall deflection ratio (i.e., deflection at wall top over wall height) can be used to specify K_a values. For moderate wall deflection ratios (i.e., 1% of wall height), K_a ranges from 0.22 to 0.25.

Typical at-rest lateral earth pressure (K_o) recommended by the Texas Department of Transportation (TxDOT) for TDA is 0.4. When active conditions are reached, the coefficient of lateral earth pressure (K_a) recommended by Tweedie et al. [1998a] is 0.25 based on the results of field tests.

Geotechnical Stability

Stability analysis can be conducted using the same methods used for conventional backfill. The overturning, sliding, bearing capacity, and global stability should be evaluated, when applicable. Typical values of shear strength of TDA backfill to be used in these analyses can be obtained from Section 3.11.

Clogging

The hydraulic conductivity of TDA is usually higher than that for sand or gravel. However, the infiltration of surrounding soil may cause clogging and this may lead to additional settlement due to added weight. To avoid such problems, properly designed filters (typically involving geotextile) may be required to prevent surrounding soils from filling TDA voids. AASHTO M 288 Class 2 (or similar) separation geotextile is recommended.

Internal Heating and Combustibility

Internal heating and combustibility of TDA fills were discussed in Section 4.6. ASTM D 6270 [ASTM, 2008] provides guidelines on minimizing the heating potential. The effectiveness of the guidelines to limit heating was demonstrated by Humphrey [2004].

As discussed in Section 4.6, the TDA fill thickness should be limited to 10 ft to avoid internal heating problems. If a TDA fill layer having a thickness greater than 10 ft is needed, the TDA fill will be broken into thinner layers separated by soil. Regarding retaining walls, the recommended design features include the following:

- cover the top and sides of the TDA fill with a 20-in. thick, compacted low-permeability soil layer;
- the topsoil layer must be sloped so that water can be drained;
- if the project is to be paved, pavement can be extended to the shoulder so that water infiltration at the edge of the pavement is minimized;
- cover drainage holes with well-graded granular soil to limit free access of air; and
- minimize as much as possible the thickness of the drainage layer at the point where it daylights on the side of the fill.

6.2.4 Case Study: Bridge Abutment, Merrymeeting Bridge, Topsham, Maine

Project Overview

TDA was used as backfill for a bridge abutment in Topsham, Maine [Humphrey, et al. 1998]. The foundation soil is 10- to 20-ft thick marine, silty sand overlying soft marine clay with thicknesses up to 50 ft. The factor of safety of the existing slope against deep-seated failure was near 1.0. The design engineer considered using a lightweight fill material to increase slope stability. Compared to other lightweight fills considered such as Geofoam® or expanded shale aggregate, TDA was considered to be the most cost-effective solution. In addition, the project made beneficial reuse of 400,000 scrap tires. In the final design, a portion of the existing slope was excavated and backfilled using 14 ft of TDA and 6 ft of soil cover. Figure 6.2 shows the longitudinal cross-section of the bridge abutment.

Construction

The surficial marine sand was partially excavated and then the abutment wall supported by H-piles was constructed. A TDA fill up to 14-ft thick was placed. Based on laboratory compressibility results, the settlement of the TDA layer was estimated to be about 18 in. under the weight of the overlying soil cover. TDA fill was overbuilt by this amount. A woven geotextile was used to separate TDA from surrounding soil. Approximately 15 in. of loose TDA was spread in each lift using front-end loaders and bulldozers. Each lift was then compacted in six passes of a smooth vibratory roller, which had a static weight of 10.4 tons. The compacted lift thickness was limited to 12 in.

Compressibility of TDA Fill

The TDA fill adjoined the bridge abutment supported by piles. The concern was that differential settlement would occur at the junction with the abutment. Field monitoring results showed that TDA fill underwent time-dependent settlement. During the placement of the overlying soil cover, the TDA fill settled about 14.6 in. The fill settled an additional 5.3 in. within 60 days of the completion of soil cover. Tweedie et al. [1997] showed that most of the time-dependent settlement occurred within the first 60 days. Therefore, the contractor was required to place an additional 1 ft of subbase aggregate as a surcharge to remain in place for a minimum of 60 days to bridge the time-dependent settlement prior to pavement construction. The surcharge was in place between October 1996 and October 1997. After October 1997, surcharge was removed and the construction of the pavement began. The highway was opened to traffic in November 2007. Between December 1996 and December 1997, the TDA fill settled about 0.6 in. The settlement rate was observed to be negligible after December 1997. The total compression of the TDA layer was 20.4 in., 13% greater than that calculated from laboratory compression test results. The final compressed unit weight was about 57 pcf.

Lateral Earth Pressures

Vibrating-wire pressure cells were installed on the back of the retaining wall to monitor lateral earth pressures at three elevations. Results are shown in Table 6.2. At completion of TDA placement, the lateral pressure was observed to increase with decreasing elevation. These findings are consistent with the results reported by Tweedie, et al. [1998a] for at-rest earth pressure conditions. However, at completion of soil cover and surcharge placement, the lateral pressure was nearly constant with depth. This is probably due to the effect of overlying weight. Because the unit weight of the overlying cover soil is much higher than that of TDA, the vertical stresses at different elevations of the TDA fill were similar.

Internal Temperature Measurement

The project was designed and built prior to the development of guidelines to limit self-ignition of TDA. The maximum fill thickness of TDA had been selected to be 14 ft, which is more than the maximum thickness of 10 ft as recommended in the guideline to limit self-ignition. Two types of TDA were used for the construction. The lower two-thirds of the TDA fill was constructed with larger size TDA (denoted as Type B by Maine DOT) that meet the design guide of ASTM D 6270. Type B TDA is specified to have a maximum size of 12 in., a minimum of 75% (by weight) passing the 8-in. sieve, a maximum of 25% (by weight) passing the 1.5-in. sieve; and a maximum of 5% (by weight) passing the No. 4 standard sieve. The upper one-third of the TDA fill (denoted as Type A) had smaller particle sizes. Type A TDA has a maximum size of 3-in. Although, Type B TDA was preferable, a larger quantity of Type A TDA was near the site. To minimize heating potential, the smaller Type A TDA was used in the upper portion of the fill. The top and sides of the fill were covered using 2 ft of fine-grained soil to limit the flow of water and air into the TDA fill. Temperature sensors were installed at three levels of the TDA fill. The highest temperature observed in the Type A TDA fill was 40°C, while the highest temperature observed from the Type B TDA fill was 29°C. This suggests that TDA with smaller particle sizes has a higher potential to self ignite. However, the observed temperatures were well below the combustion limit.

6.3 Highway Embankment Fill

6.3.1 Application Overview

TDA is usually used as a lightweight fill in highway embankments. Compared to other lightweight fill materials (e.g., Geofoam®), TDA has proven in various projects to be the material with the lowest cost. The low unit weight of TDA reduces driving forces and hence increases slope stability. TDA also reduces the weight of embankment, thereby reducing settlement if the embankment is on soft soils. When founded on weak soil, TDA helps to avoid failure due to insufficient bearing capacity. Using TDA as lightweight fill has proven to be a good solution for road embankments built on top of soft ground. Minnesota and Maine DOTs have extensive experience using TDA for road embankment constructed over soft ground.

Another application of TDA in highway embankment fill is insulation of subbases and bases from frost penetration in cold climates. Frost penetration beneath roads when uncontrolled can lead to bumpy driving conditions and cracking of pavement. TDA is a good solution to this problem because the thermal conductivity of TDA is significantly lower than that of common soils.

6.3.2 General Material Requirements

The specifications provided by Minnesota DOT require that: (i) 80% of TDA pass the 8-in. sieve; (ii) 50% of TDA pass the 4-in. sieve; (iii) the maximum dimension of TDA particles be less than 24 in.; and (iv) 98% of weight of the metal be embedded in the tire rubber.

Specifications recommended by Humphrey [2006b], as provided in Section 6.2.2 for TDA used as retaining wall backfill, can also be used as guidance for selection of TDA material for use as embankment fills.

6.3.3 Performance Considerations

Clogging

To prevent the infiltration of surrounding soils and protective physical clogging, TDA fill should be completely wrapped in geotextiles. AASHTO M 288 Class 2 separation geotextile is recommended.

Compressibility and Overlying Soil Cover

Due to the high compressibility of TDA, overlying soil covers with an adequate thickness is necessary to limit deflection at the surface. The tensile strain at the bottom of the pavement is also an important design consideration. High-tensile strains occurring when significant differential settlement takes place will lead to a reduced service life. The University of Maine monitored the pavement deflection in two field trials [Nickels, 1995], and observed that the settlement of the control section with soil cover above TDA was larger than the control section without TDA. In general, as the thickness of the soil cover increases, localized pavement deflection decreases. The section with TDA particles smaller than 12 in. showed larger deflections than the section with smaller TDA particles (i.e., smaller than 3 in.). The size of the deflected area in the TDA section was also larger than that for the control section. This result indicates that the tensile strain at the bottom of a pavement with TDA may show a modest increase. Humphrey and Nickels [1997] studied the effect of cover thickness on the maximum tensile strain at the bottom of the pavement. The results are summarized in Table 6.3. These results indicate that if the soil cover thickness was greater than 18 in., the maximum tensile strains at the TDA section would be similar to that for all soil control sections.

Humphrey [2006a] recommended thickness of overlying cover soil as follows. For asphalt/concrete pavements with high modulus (i.e., relatively rigid, pavement modulus equal to approximately 1,000,000 psi), a soil cover thicker than 3 or 4 ft was suggested. For asphalt/concrete pavements with low modulus (i.e., relatively flexible, pavement modulus equal to approximately 40,000 psi), a minimum thickness of 2 ft was suggested. Minnesota DOT (MnDOT) suggested using 5 to 6 ft of soil cover for major roads [MnDOT, 2005]. For unpaved, low-volume roads, soil cover with thicknesses as low as 18 in. have been built in Minnesota. However, performance was not fully evaluated.

For unpaved road, the main function of soil cover is to prevent rutting. The required thickness of soil cover depends on the traffic volume and the thickness of the TDA fill. Humphrey [1997] reported successful usage of 12 in. of soil cover over 6 in. of TDA fill and 18 in. of soil cover over 12 in. of TDA fill. For thin soil covers, surface deflection of unpaved road will be evident initially, but the deflection rate will decrease with traffic loads applied over time. It is recommended that a minimum of 18 in. of soil cover be used for unpaved road.

Thermal Conductivity and Frost Insulation Layers

When TDA fill is used as a frost insulation layer, the design can be conducted using the method given by Aldrich [1956]. In addition to the thermal properties of TDA, soil cover, pavement, and subgrade soil, the freezing index at the project location is needed to estimate the depth of frost penetration. In Maryland, frost insulation is not a critical application of TDA because of its relatively warm climate.

6.3.4 Case Study: Portland Jetport [Humphrey, et al., 1998]

Project Overview

TDA was used as lightweight fill for construction of two 32-ft high highway embankments in Portland, Maine. These embankments were approach fills to a new bridge over the Maine Turnpike, near the Portland Jetport. This site was underlain by about 40 ft of weak marine clay, which is over-consolidated, moderately sensitive, inorganic, and of low plasticity. The undrained shear strength of the clay varied from approximately 1,500 psf (near the top) to 400 psf near the center of the layer. If built using conventional fill, the factor of safety of the embankment would have been unacceptably low. Three options were considered: (i) construction of stabilizing berms; (ii) ground improvements; and (iii) use of lightweight fill. Construction of stabilizing berms were eliminated because of impact to nearby wetlands. Ground improvement techniques were discarded because of the high cost. Eventually, lightweight fill was selected. The lightweight fill that was considered included TDA, expanded polystyrene insulation boards, and expanded shale. TDA was selected because it was $300,000 cheaper than the other options. In addition, the project beneficially reused 1.2 million tires. Wick drains were also installed to accelerate consolidation of the foundation soils.

Stability analysis indicates that 20 ft of TDA fill was required to reach the desired factor of safety. However, the design guidelines to minimize heating provided in the ASTM D 6270 Standard suggest that the thickness of TDA fill should be less than 10 ft. Therefore, the TDA fill was divided into two layers, each up to 10-ft thick and separated by 3 ft of low-permeability fill. The embankment was topped with 2 ft of low-permeability fill and 4 ft of subgrade gravel. Additionally, 4 ft of temporary fill was applied to the top as surcharge to accelerate the consolidation of marine clay. Figure 6.3 shows the cross-section of the embankment.

Heating

Several measures were employed to minimize heating potential. As stated above, the 20-ft TDA fill was divided into two layers to minimize heating. Relatively large size TDA particles with little to no fines were used (e.g., TDA particles with less than 25% passing the 1½-in. sieve and less than 1% passing the No. 4 sieve). The maximum particle size measured was 12 in. to ensure that TDA could be easily placed using conventional construction equipment. Low-permeability soil with a minimum of 30% fines (passing the No. 200 sieve) was placed on the outside and on top of the fill to limit the inflow of air and water. Temperature data obtained within the TDA fill showed a decreasing trend until the monitoring ended in April 1998, indicating no heating problem.

Construction

Tires for this project came from an abandoned stockpile in Durham, Maine. The Maine Turnpike Authority and the Maine Department of Environmental Protection shared the cost to produce the tire shreds and deliver them to the construction site. The tire shreds were produced by J.P. Routhier & Sons of Ayer, Massachusetts, and Arthur Schofield, Inc. of Lancaster, Massachusetts. At peak production, four shredding machines operated at the stockpile site. The shredding machines had knife spacings ranging from 2 to 6 in. A rotating screen (i.e., trommel) with 6-in. square openings was used to capture pieces that exceeded the 12-in. maximum length criterion for recirculation back through the shredders. As the source tires contained a significant amount of soil, the contractor had to use the trommel with 0.5-in. openings to produce shreds with less than 1% passing the No. 4 sieve.

The tire shreds were placed using conventional construction techniques. First, geotextile was placed on the prepared base as a separator between the tire shreds and underlying soil. Then, the tire shreds were spread out in 12-in. thick lifts using a Caterpillar D-4 dozer. Each lift was compacted with six passes of a vibratory roller with a minimum 10-ton operating weight. After placing the shreds, the contractor placed a geotextile separator on the sides and top of the tire shred zone. Finally, soil cover was placed.

Settlement

Settlement plates, installed at the top and bottom of each TDA fill layer, were used to monitor settlement. Monitoring data showed very little time-dependent settlement. The upper TDA layer settled about 5 to 21 in. after approximately five months at full load. Settlement of the lower layer varied from 5 to 18 in. The compression of the TDA layer was similar to the settlement of the foundation soil, which settled 2 to 15 in. during the same period.

6.4 Septic Drainage Media

6.4.1 Application Overview

Conventional septic systems consist of a septic tank and a leach field. The septic tank is a temporary storage for sewer waste, where wastewater is separated from heavy solids and lighter grease or oil. Wastewater then flows through the leach field, which typically is a trench filled with coarse aggregate. Biofilms developed on the surface of the aggregate in the leach field help purify the wastewater. Furthermore, wastewater is distributed into the surrounding soil, where the wastewater seeps in and is then decomposed by bacteria living in the soil. After this process, the sewage returns to the groundwater. TDA can be used as a drainage media in the leach field in a septic system. The functions of the septic leach field drainage media are to: (i) provide effective and reliable distribution of the liquid wastewater to the surrounding soil; and (ii) provide a medium onto which biofilm develops to assist in the removal of oxygen-demanding wastes. The waste demand includes 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), ammonia-nitrogen, and nitrate.

At present, several states, such as Georgia, Iowa, North Carolina, South Carolina, Texas, and Virginia, have permitted the use of TDA as a substitute drainage medium in conventional septic leach field systems. The successful application of this alternative is based on numerous laboratory and field studies that primarily investigated the potential leachability of contaminants deriving from TDA and the potential impact to groundwater quality [Envirologic, 1990; Zelibor 1991; Daniels and Bird, 1993; Liu et al., 1998; Sengupta and Miller, 1999, 2000, and 2004; Amoozegar and Robarge, 1999; Spagnoli et al., 2001; Weber and Kim, 2002; and Grimes et al., 2003]. In Maryland, MDE regulates the design of septic leach field systems.

6.4.2 General Material Requirements

The following material properties of TDA must be considered for its use as an alternative drainage medium for septic drainage:

- size and wire exposure;
- porosity; and
- hydraulic conductivity.

Gradation

The size of TDA used for septic drainage material typically ranges from 0.5 to 4 in. North Carolina and Virginia guidelines require that TDA particles should have a nominal size of

2 in. and may range from 0.5 to 4 in. in any dimension. Texas guidelines recommend using TDA particles less than 2 in. Most guidelines require that no fines be present and that the exposed belt or bead wires should protrude no more than 0.5 in. from the chip. The TDA gradation requirement from different state guidelines is summarized in Table 6.4. In general, TDA used for septic tank leach field should meet the requirements for Class I fills in ASTM D 6270 [ASTM, 2008], which is presented in Section 4.6.

Porosity

Porosity is an important property of septic leach field materials because it is related to storage capacity. When a sudden influx of wastewater enters the leach field system, adequate storage at least equivalent to that provided by gravel is required. Envirologic [1990] estimated that TDA with nominal 2-in. sizes has porosity of approximately 0.60, while the porosity of 0.75-in. to 1.5-in. size crushed stone is approximately 0.40. This indicates that TDA provides comparable or greater storage volume than crushed stone.

Hydraulic Conductivity

As previously discussed in Section 3.9, the hydraulic conductivity of TDA varies from 0.01 to 60 cm/sec, which is generally greater than that for sands and gravels. Therefore, from a material property equivalency perspective, the use of TDA is an acceptable alternative. In addition, compressibility is not considered an issue due to low overburden pressures.

In terms of hydraulic performance under field conditions, Weber and Kim [2002] evaluated parallel trenches utilizing TDA or stone by measuring water levels in the trenches over a period of about 20 months. They concluded that TDA provides acceptable hydraulic performance as a septic drainage medium.

6.4.3 Performance Considerations

The following aspects must be considered for the use of TDA as an alternative drainage material:

- biofilm formation (clogging);
- combustibility potential;
- leachability (groundwater pollution potential); and
- constructability.

These aspects are discussed as follows.

Biofilm Formation

The formation of a biofilm (or biomat) on the aggregate layer in the septic leach field system develops into a subsystem that facilitates the degradation of oxygen-demanding wastes. Grimes et al. [2003] and Sengupta and Miller [2004] provided field data showing the formation of a biomat on TDA septic leach field systems. The overall conclusion of these field studies was that septic leach fields that use TDA perform as well as conventional septic leach fields that use gravel.

One difference with the conventional system is that formation of the biomat on TDA would take about 30 to 60 days longer than on conventional soils [Sengupta and Miller, 2004]. This may be attributed to the smoother surface associated with TDA in comparison to a rougher gravel surface, thereby providing little resistance to shear for the biomat layer. As a result, the gravel layer will form an equilibrium biomat thickness in a shorter time.

Internal Heating and Combustibility Potential

As discussed in Section 4.6, under extreme conditions where the heat generation rate is higher than the dissipation rate, combustibility of TDA can be a problem if internal heating temperatures reach the auto-ignition point of approximately 550° to 650°F. To prevent the internal heating potential of TDA layers, ASTM D 6270 guidelines recommend that TDA fill layers do not exceed 10-ft thick. Given the typical thickness of TDA layers in septic leach field systems, internal heating and combustibility are not a concern.

Leachability Potential

The two primary concerns of utilizing TDA as drainage media in septic leach field systems are: (i) the potential release of contaminants deriving from TDA; and (ii) the resulting impact on groundwater quality. In an effort to address these issues, several studies have been conducted under a variety of laboratory and field conditions [Envirologic, 1990; Zelibor 1991; Daniels and Bird, 1993; Liu et al., 1998; Sengupta and Miller, 1999, 2000, and 2004; Amoozegar and Robarge, 1999; Spagnoli et al., 2001; Weber and Kim, 2002; and Grimes et al., 2003]. The primary findings are summarized below.

Sengupta and Miller [2003] presented results from pilot test leaching-field trenches constructed using both gravel and TDA. Results indicated that TDA trenches do not leach any toxic metal or inorganic anion with a concentration greater than the secondary drinking water standard maximum contaminant level (MCL) except for manganese (Mn). However, this release did not appear to be the result of TDA because manganese concentration in effluent from the gravel trenches also exceeded the MCL for secondary drinking water standard. TDA trenches did not leach any toxic metals or inorganic anions that have a concentration higher than that of the gravel trench. Doak [1999, 2000, and 2001] reported water quality results for both TDA and gravel trenches constructed for a demonstration project of septic systems. The concentrations of inorganic compounds from the TDA trench effluent were found to be less than that from the gravel trench effluent, and were below the groundwater protection standard. However, the concentration of perchloroethene (PCE, a solvent used in numerous cleaning products), which was introduced by the contaminated TDA, was slightly higher than the groundwater protection standard.

Section 4.7 contains an overview of potential groundwater contamination induced by TDA. In general, TDA may leach metals such as iron (Fe), manganese (Mn) at elevated concentration levels when placed below the groundwater table. In general, the release of organics from TDA placed above the groundwater table is below method detection limits [Humphrey and Katz, 2000] and is not a significant concern. TDA placed below the groundwater table releases trace levels of a few volatile and semivolatile organics. However, samples taken a few feet downgradient show that the effects are reduced to negligible levels. Hence, TDA placed below the groundwater table have negligible effects for off-site water quality.

Constructability

Constructability issues associated with the placement of TDA in septic leach fields are: (i) compaction and post-construction settlement; and (ii) clogging. These two topics were discussed in detail in Section 4 with respect to TDA landfill applications.

At low overburden pressures and for the relatively thin layers of TDA septic leach fields, the post-construction settlement can be greatly reduced or eliminated with proper compaction. A separation geotextile is recommended over the top of the TDA layer to prevent infiltration of fines and clogging due to the backfill soil above the septic leach field system. Several states require a separation geotextile even for conventional aggregate.

6.4.4 Case History: Weld County, Colorado

Two TDA septic systems were installed in Weld County, Colorado, as part of a demonstration project [Doak, 1999, 2000, and 2001]. Each system serves a single-family home and consists of a tank and a distribution box. The leach field was equally divided into TDA and rock aggregate trenches. Sampling ports were installed in both rock aggregate and TDA trenches to collect effluent samples discharged from the septic system. Two sampling ports were installed in each trench. The first system was put into use in April 1998 and the second became active in early spring 2000. Figure 6.4 shows a sketch of the sampling ports and cross-section of the trench.

Effluent was sampled every three months after the first system became active. Liquid was observed in both sampling ports in the TDA trench, whereas for the rock aggregate trench liquid was not observed in the sampling port further away from the distribution box. Possible explanations are: (i) the rock aggregate had a larger capacity for storing the liquid; (ii) the distribution line may have settled and may have prevented the liquid from flowing to the end of the rock aggregate trench. Elements detected from the samples included barium, lithium, copper, iron, manganese, vanadium, and zinc. Samples obtained from the rock trench were observed to have higher concentrations of these elements than those obtained from the TDA trench. The concentrations of total suspended solids measured from TDA trench effluent samples were 10 to 50 times higher than those measured from rock trench effluent samples. However, the concentrations of these inorganic compounds were below the groundwater protection standard. The concentration of PCE was slightly higher than the groundwater protection standard. It was determined that the PCE was not from the sewer, but from the contaminated TDA themselves. Besides PCE, other inorganic compounds detected included trichloroethene (TCE), 4-methyl-2-pentanone, cis-1,2-dichloroethene (cis-1,2-DCE). Samples taken at a later time showed a decrease in PCE concentration. However, some results obtained at least 6 months after the system started functioning, showed a medium to high level of cis-1,2-DCE for the first time. This was attributed to the transformation of TCE to PCE to cis-1,2-DCE under anaerobic (without oxygen) conditions.

Based on the success of the demonstration project, TDA was approved for use in septic drainage fields in Colorado.

7. OTHER APPLICATIONS OF TDA

7.1 Introduction

Scrap tires can also be turned into ground rubbers (particle size less than 0.5 in.), which can be used for asphalt rubbers or commercially manufactured products. A brief overview of these applications is presented as follows.

7.2 Asphalt Rubber

Asphalt rubber (as produced using the so called wet process) is defined by ASTM D8 [2008] as: "*a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15% by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles*". Asphalt rubber has been used in the United States since the early 1960s. Arizona, California, and Texas are the main users of this technology. Other products often referred to as rubberized asphalt, have also been used. These products include the "dry process", where crumb rubber is added during the mixing operation and the crumb rubber does not fully react with the asphalt. In the "terminal blend process", the crumb rubber is "aggregated" into the asphalt cement at the asphalt plant. The "terminal blend process" typically uses half of the amount of tire rubbers as the wet or dry processes. In Maryland, demonstration projects were completed in Talbot County on roads and parking lots between May and September 2006. The performance of asphalt rubber pavement is considered satisfactory by Talbot County.

The benefits of asphalt rubber include:

- improves the resistance to skid and helps to reduce noise levels;
- helps to improve the resistance to rutting and prevents cracking in new pavements;
- provides excellent, long-lasting color contrast for striping and marking;
- reduces reflective cracking in asphalt overlays (i.e., cracks appearing in new, thin overlays that are identical to cracks present in existing pavement) and provides a long-lasting and durable pavement;
- helps reduce maintenance costs; and
- a 2-in. resurfacing layer constructed with asphalt rubber results in the beneficial use of over 2,000 tires per mile (one lane).

The limitations of these products include:

- odor and air quality problems;
- more labor requirements;
- unit cost is higher than traditional pavement, although the annual cost within the life cycle is lower; and
- construction cannot occur in cold weather.

7.3 Playground Cover

Playground cover made from tire chips offers some advantages because it provides good shock absorption capacity, which helps protect children from injury. TDA in playground covers drains well after rain. TDA is clean and does not attract insects or small animals. TDA does not decompose and is easy to maintain. As long as the tire chips have been properly cleansed, TDA is non-toxic and safe to children. Birkholtz et al. [2003] conducted a comprehensive hazard assessment to evaluate the impact of scrap tire in playground covers on human health and the environment. Hazard analyses and toxicity tests of extracted tire crumb indicate a tolerable hazard to human health. Some states (e.g., California and Missouri) have established grants to promote the use of playground cover made from scrap tires.

7.4 Commercially Manufactured Products

A wide range of commercial products manufactured from scrap tires are available in the market. A list of manufacturers and vendors are included in Appendix C. Representative applications are summarized below.

Modular Rubber Sidewalk

A company in California manufactures modular sidewalks made with recycled tire rubber. This product has been used by several municipalities in California and several states in the eastern U.S., including the City of Baltimore.

The pavement modules (i.e., pavers) are interconnected and can be periodically opened for tree root maintenance. The material has a high coefficient of friction under both wet and dry conditions, which minimizes trip hazard. Additionally, pavers are durable and easy to maintain.

Rubber Mulch

There are several rubber mulch products on the market. Some of these are tire rubber entirely and others combine tire chips and compost. These products are used for landscaping and playgrounds. In landscaping, rubber mulch helps to aerate the soil. In addition, rubber mulch provides an alternative to typical cypress, pine, and other wood mulches, which decompose easily and must be replenished and replaced. Rubber mulch is clean and safe to plants and aesthetically pleasant, and does not harbor insects.

Modular Rubber Drain

A company in California (Modular Rubber Drains, Inc., Goshen, California) manufactures modular rubber drain made from scrap tires. These modular drains are easy to install and can be interconnected. A typical application of modular rubber drains is roadside drainage channel.

Other Molded Products

Granulated rubber has been used in a range of molded products including speed bumps, wheel chocks, soaker hoses, and doormats.

Automotive Parts

Scrap tires can be used to manufacture new tires (up to 10% or higher according to scraptirenews.com), brake pads and brake shoes, etc.

8. REFERENCES

Ahmed, I. [1993]. "*Laboratory Study on Properties of Rubber Soils*", Report No. FHWA/IN/JHRP-93/4, Purdue University, West Lafayette, Indiana.

Aldrich [1956]. "*Frost Penetration Below Highway And Airfield Pavements*", Highway Research Board Bulletin 135, National Research Council, Washington, D.C., pp. 124-144.

Amoozegar, A. and Robarge, W.P. [1999]. "*Evaluation of Tire Chips as a Substitute for Gravel in the Trenches of Septic Systems*", prepared for the Division of Pollution Prevention and Environmental Assistance, Department of Environment and Natural Resources, State of North Carolina.

Andrews, D.W. and Guay, M.A. [1996]. "*Tire Chips in a Superfund Landfill Cap: A Case History of the First Use of a Tire Chip Drain Layer*", Proceedings, Nineteenth Annual Madison Waste Conference, University of Wisconsin-Madison, Madison, Wisconsin.

ASTM [2008]. "*Annual Book of ASTM Standards*", American Society for Testing and Materials, West Conshohocken, Pennsylvania.

Aydilek, A.H., Madden, T.E., and Demirkan [2005], "*Field Evaluation of a Leachate Collection System Constructed with Scrap Tires*", University of Maryland, College Park, Maryland.

Barris, D.C. [1987]. *Report of Ground & Surface Water Analyses*. Unpublished Report, Environmental Consulting Laboratory.

Beatty, J.R. [1981]. "*Physical properties of rubber compounds*". Mechanics of Pneumatic Tires, S.K. Clark, ed., United States Department of Transportation, National Highway Traffic Administration, Washington, D.C.

Benda, C.C. [1995]. "*Engineering Properties of Scrap Tires Used in Geotechnical Applications*", Report 95-1, Materials and Research Division, Vermont Agency of Transportation, Montpelier, Vermont.

Bernal, A. [1996]. "*Laboratory Study on the Use of Tire Shreds and Rubber-Sand in Backfills and Reinforced Soil Applications*", Report No.: FHWA/IN/JHRP-96/12, School of Civil Engineering, Purdue University, West Lafayette, Indiana.

Bernal, A., Salgado, R., Swan, Jr., R.H., and Lovell, C.W. [1997]. "*Interaction Between Tire Shreds, Rubber-Sand and Geosynthetics*", Geosynthetics International, Vol. 4, No. 6, pp. 623-643.

Birkholz, D.A., Belton, K.L., and Guidotti, T.L. [2003]. "*Toxicological Evaluation for the Hazard Assessment of Tire Crumb for Use in Public Playgrounds*". Journal of the Air & Waste Management Association, July 2003, Vol. 5, pp. 903-907.

Bosscher, P.J., Edil, T.B., and Eldin, N. [1993]. "*Construction and Performance of Shredded Waste Tire Embankments*", Transportation Research Record, 1345, pp. 44-52, National Research Council, Transportation Research Board, Washington, D.C.

Bosscher, P.J., Edil, T.B., and Kuraoka, S. [1997]. "*Design of Highway Embankments Using Tire Chips*", Journal of Geotechnical and Geoenvironmental Engineering, Vol. 123, No. 4, April, pp. 295-304.

Bressette, T. [1984]. "*Used Tire Material as an Alternative Permeable Aggregate*", Report No. FHWA/CA/TL-84/07, Office of Transportation Laboratory, California Department of Transportation, Sacramento, California.

Chu, C-J. [1998]. "*A Geotechnical Investigation of the Potential Use of Shredded Scrap Tires in Soil Stabilization*", Ph.D. Dissertation, Kent State University, Kent, Ohio.

Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA), 42 U.S.C. §§ 9601-9675 [2001].

Cosgrove, T.A. [1995]. "*Interface Strength Between Tire Chips and Geomembrane for Use as a Drainage Layer in a Landfill Cover*", Proceedings, Geosynthetics '95 Conference, Vol. 3, Industrial Fabrics Association, Nashville, Tennessee.

Daniels, J. and Bird, B. [1993]. "*A Report on the Use of Scrap Tire Shreds as Soil Absorption Media*", prepared for the Kansas Department of Health and Development, Leavenworth, Kansas.

Dickson, T.H., Dwyer, D.F., Humphrey, D.N. [2001]. "*Prototype Tire-Shred Embankment Construction*", Transportation Research Record, 1755, National Research Council, Transportation Research Board, Washington, D.C. , pp. 160-167.

Doak, R. [1999]. "*Study May Provide New Market and Recycling Opportunity for Tires*". Solid Waste News & Notes, Colorado Department of Public Health and Environment, Denver, Colorado. Vol. 2, No. 1, pp. 5.

Doak, R. [2000]. "*Not Tired Yet: An Update on the Scrap Tire Demonstration Project*". Solid Waste News & Notes, Colorado Department of Public Health and Environment, Denver, Colorado. Vol. 3, No. 1, pp. 4.

Doak, R. [2001]. "*Washed Tires Produce Cleaner Effluent: Third in a Series of Articles Discussing the Scrap Tire Septic System Demonstration Project*". Solid Waste News & Notes, Colorado Department of Public Health and Environment, Denver, Colorado. Vol. 4, No. 1, pp. 5.

Donovan, R., Dempsey, J. and Owen, S. [1996]. "*Scrap Tire Utilization in Landfill Applications*", Proceedings, WASTECON 1996, Portland, Oregon.

Downs, L.A. [1996]. "*Water Quality Effects of using Tire Chips Below the Groundwater Table*", M.S. Thesis, Department of Civil and Environmental Engineering, University of Maine, Orono, Maine.

Drescher, A., Newcomb, D., and Heimdahl, T. [1999]. "*Deformability of Shredded Tires*", Minnesota Department of Transportation, January, pp. 145.

Duffy, D.P. [1996]. "*The Potential for Use of Shredded Tire Chips as a Leachate Drainage and Collection Medium: Design, Construction and Performance Considerations*", Proceedings, Landfill Design Seminar Using Tire Shreds, Texas Natural Resource Conservation Commission (TNRCC), Arlington, Texas.

Ealding, W. [1992]. "*Final Report on Leachable Metals in Scrap Tires*", Virginia Department of Transportation Materials Division, Virginia Department of Transportation Scrap Tire Task Force.

Edil, T.B., and Bosscher, P.J. [1992]. "*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, Wisconsin, November.

Edil, T.B., Fox, P.J. and Ahl, S.W. [1992]. "*Hydraulic Conductivity and Compressibility of Waste Tire Chips*", Proceedings, Fifteenth Annual Madison Waste Conference, University of Wisconsin-Madison, Madison, Wisconsin.

Envirologic, Inc. [1990]. "*A Report on the Use of Shredded Scrap Tires in On-site Sewage Disposal Systems*", prepared for the Department of Environmental Conservation, State of Vermont, Brattleboro, Vermont.

Geosyntec Consultants, Inc. [1997]. "*Report of Tire Chip Protective Layer Monitoring System Installation, Scrap Tire Demonstration Project, Newland Park Landfill, Wicomico County, Maryland"*, prepared for the Maryland Environmental Service, Annapolis, Maryland.

Geosyntec Consultants, Inc. [1998a]. "*Tire Shreds as Cover Foundation, Leachate Drainage and Operations Layer Material at Municipal Solid Waste Landfills*", prepared for the California Integrated Waste Management Board, Sacramento, California.

Geosyntec Consultants, Inc. [1998b]. "*Tire Shreds as Gas Collection Material at Municipal Solid Waste Landfills*", prepared for the California Integrated Waste Management Board, Sacramento, California.

Geosyntec Consultants, Inc. [1998c]. "*Tire Shreds as Final Cover Foundation Layer Material at Municipal Solid Waste Landfills*", prepared for the California Integrated Waste Management Board, Sacramento, California.

Geosyntec Consultants, Inc. [1998d]. "*Tire Shreds as Leachate Drainage Material at Municipal Solid Waste Landfills*", prepared for the California Integrated Waste Management Board, Sacramento, California.

Geosyntec Consultants, Inc. [1998e]. "*Tire Shreds as Operations Layer Material at Municipal Solid Waste Landfills*", prepared for the California Integrated Waste Management Board, Sacramento, California.

Geosyntec Consultants, Inc. [2002]. "*Final Report: Scrap Tire Demonstration Project, Newland Park Landfill, Wicomico County, Maryland"*, prepared for Maryland Environmental Service, Inc.

Geosyntec Consultants, Inc. [2004]. "*Report of Tire Chip Excavation and Laboratory Testing,, Scrap Tire Demonstration Project, Newland Park Landfill, Wicomico County, Maryland"*, prepared for Maryland Environmental Service, Annapolis, Maryland.

Giroud, J.P., Williams, N.D., Pelte, T. and Beech, J.F. [1995]. "*Stability of Geosynthetic-Soil Layered Systems on Slopes*", Geosynthetics International, Vol. 2, No. 6.

Grimes, B.H., Steinbeck, S. and Amoozegar, A. [2003]. "*Analysis of Tire Chips as a Substitute for Stone Aggregate in Nitrification Trenches of Onsite Septic Systems: Status and Notes on the Comparative Macrobiology of Tire Chips Versus Stone Aggregate Trenches*", Small Flows Quarterly, Vol. 4, No. 4.

Hall, T.J. [1991]. "*Reuse of Shredded Tire Material for Leachate Collection Systems*", Proceedings, Fourteenth Annual Madison Waste Conference, University of Wisconsin-Madison, Madison, Wisconsin.

Holtz, R.D. and Kovacs, W.D. [1981]. "*An Introduction to Geotechnical Engineering*", Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 733 p.

Humphrey, D.N. [1996a]. "*Engineering Properties and Water Quality Effects of Tire Chips for Landfill Construction*", Proceedings, Seminar on Landfill Design Using Tire Shreds, Texas Natural Resource Conservation Commission, Arlington, Texas.

Humphrey, D.N. [1996b]. "*Investigation of Exothermic Reaction in Tire Shred Fill Located on SR 100 in Ilwaco, Washington*", prepared for Federal Highway Administration, Washington, D.C.

Humphrey, D.N. [2001]. "*Material Specifications for Use of Tire Derived Aggregate (TDA) in Civil Engineering Applications*", University of Maine, Orono, Maine.

Humphrey, D.N. [2002]. "*Calculation of Overbuild*", University of Maine, Orono, Maine.

Humphrey, D.N. [2004]. "*Effectiveness of Design Guidelines for use of Tire Derived Aggregate as Lightweight Embankment Fill*". Recycled Materials In Geotechnics, ASCE, pp. 61-74.

Humphrey, D.N. [2006a]. "*Civil Engineering Applications of Tire Derived Aggregate*", Course Notes, prepared for California Integrated Waste Management Board.

Humphrey, D.N. [2006b]. "*Material Specifications for Use of Tire Derived Aggregate (TDA) in Civil Engineering Applications - Revised*", University of Maine, Orono, Maine.

Humphrey, D.N. and Katz, L.E. [2000]. "*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, D.C., pp. 18-24.

Humphrey, D.N. and Katz, L.E. [2001]. "*Field Study of Water Quality Effects of Tire Shreds Placed Below the Water Table*", Proceedings of the Conference on Beneficial Use of Recycled Materials in Transportation Applications, Air and Waste Management Association, Pittsburgh, Pennsylvania.

Humphrey, D.N. and Manion, W.P. [1992]. "*Properties of Tire Chips for Lightweight Fill*", Grouting, Soil Improvement and Geosynthetics, R.H. Borden, et al., eds., ASCE, Vol. 2, pp. 1344-1355.

Humphrey, D.N., and Nickels, W.L., Jr. [1997], "*Effect of Tire Shreds as Lightweight Fill on Pavement Performance*", Proceedings of the 14th International Conference on Soil Mechanics and Foundation Engineering, Vol. 3, pp. 1617-1620.

Humphrey, D.N. and Sandford, T.C. [1993]. "*Tire Chips as Lightweight Subgrade Fill and Retaining Wall Backfill*", Proceedings, Symposium on Recovery and Effectiveness Reuse of Discarded Materials and By-Products for Construction of Highway Facilities, FHWA, U.S. Department of Transportation, Washington, D.C.

Humphrey, D.N. and Swett, M. [2006]. *"Literature Review of the Water Quality Effects of Tire Derived Aggregate and Rubber Modified Asphalt Pavement"*, prepared for USEPA Resource Conversion Challenge, University of Maine, Orono, Maine.

Humphrey, D.N., Chen, L.H., and Eaton, R.A. [1997a]. "*Laboratory and field measurement of the thermal conductivity of tire chips for use as subgrade insulation*", Preprint No. 971289, Transportation Research Board, Washington, D.C.

Humphrey, D.N., Katz, L.E., and Blumenthal, M. [1997b]. "*Water Quality Effects of Tire Chip Fills Placed Above the Groundwater Table*", ASTM STP 1275, American Society of Testing Materials, West Conshohocken, Pennsylvania.

Humphrey, D.N., Sandford, T.C., Cribbs, M.M., Gharegrat, H., and Manion, W.P. [1992]. *"Tire Chips as Lightweight Backfill for Retaining Walls–Phase I"*, prepared for the New England Consortium, 137 pp.

Humphrey, D.N., Sandford, T.C., Cribbs, M.M., and Manion, W.P. [1993]. *"Shear Strength and Compressibility of Tire Chips for Use as Retaining Wall Backfill"*, Transportation Research Record, No. 1422, Transportation Research Board, p.p. 29-35.

Humphrey, D.N., Whetten, N., Weaver, J., Recker, K., Cosgrove, T.A. [1998]. "*Tire Shreds as Lightweight Fill for Embankments and Retaining Walls*", ASCE Geotechnical Special Publication No. 79, ASCE, Reston, Virginia.

Jesionek, K.S., Humphrey, D.N., and Dunn, R.J. [1998]. "*Overview of Shredded Tire Applications in MSW Landfills*", Proceedings, The Tire Industry Conference, Clemson University, Clemson, South Carolina.

Koerner, R.M. [1998]. "*Designing with Geosynthetics*", 4th Ed., Prentice-Hall, New Jersey.

Kulhawy, F.H. and Mayne, P.W. [1990]. *Manual on estimating soil properties for foundation design*. Final Report 1493-6, EL-6800, Electric Power Research Institute, Palo Alto, California.

Lamb, T.W. and Whitman, R.V. [1969]. *Soil Mechanics*. John Wiley & Sons, New York.

Lawrence, B.K., Chen, L.H., and Humphrey, D.N. [1998]. "*Use of Tire Chip/Soil Mixtures to Limit Frost Heave and Pavement Damage of Paved Roads*", A Study for the New England Transportation Consortium, by the Department of Civil and Environmental Engineering, University of Maine, Orono, Maine, 316 pp.

Liu, H.S., Mead, J.L., and Stacer, R.G. [1998]. "*Environmental Impacts of Recycled Rubber in Light Fill Applications: Summary and Evaluation of Existing Literature*", Technical Report No. 2, Chelsea Center for Recycling and Economic Development, University of Massachusetts, Chelsea, Massachusetts.

Marella, A. [2002]. "*Use of Shredded Scrap Tires as Drainage Material in Landfill Covers*", M.S. Thesis, University of Illinois at Chicago, Chicago, Illinois.

MDE [2004a]. (http://www.mde.state.md.us/Programs/LandPrograms/Recycling/ScrapTire/program.asp).

MDE [2004b]. (http://www.mde.state.md.us/Programs/LandPrograms/Recycling/ScrapTire/licenses.asp).

MnDOT [2005]. "*Official Mn/DOT Standard of Engineering Practice for the use of Shredded Tires in Roadways (pursuant to MN Statute 115A.912, Subdivision 4*)", Minnesota Department of Transportation.

Narejo, D.B., Shettima, M. [1995]. "*Use of Recycled Automobile Tires to Design Landfill Components*", Geosynthetics International, Vol. 2, No. 3, pp. 619-625.

NFPA [1998], "*NFPA 231D Standard for Storage of Rubber Tires*", National Fire Protection Association, Quincy, Massachusetts.

Nickles, W.L., Jr. [1995]. "*The Effect of Tire Shreds as Subgrade Fill on Paved Roads*", M.S. Thesis, Department of Civil Engineering, University of Maine, Orono, Maine.

Ohio Environmental Protection Agency [2000]. "*Use of Shredded Tires in Landfill Construction*", DSIWM-00-00-0599, OEPA, Division of Solid and Infectious Waste Management.

Park, J.K., Edil, T.B., Kim, J.Y., Huh, M., Lee, S.H., and Lee, J.J. [2003]. "*Suitability of Shredded Tires as a Substitute for a Landfill Leachate Collection Medium*", Waste Management and Research, Vol. 21.

Phaneuf, R. and Glander, C. [2003]. "*Using Tire Chips in Landfill Leachate Collection and Removal Systems Under 6 NYCRR Part 360*", Proceedings, Federation of New York Solid Waste Associations, 2003 Solid Waste/Recycling Conference and Trade Show, Bolton Landing, New York.

Reddy, K.R. and Saichek, R.E. [1998]. "*Assessment of Damage to Geomembrane Liners by Shredded Scrap Tires*", Geotechnical Testing Journal, American Society for Testing and Materials, Vol. 21, Issue 4, pp. 307–316.

Richardson, G.N., Giroud, J.P., Zhao, A. [2000]. "*Design of Lateral Drainage Systems for Landfills*", Tenax Corporation Design Manual, Tenax Corporation, Baltimore, Maryland.

RMA [2006]. "*Scrap Tire Markets in the United States, 2005 Edition*", Rubber Manufacturers Association, Washington, D.C., November.

Rowe, R.K. and Mclsaac, M. [2005]. "*Clogging of Tire Shred and Gravel Permeated with Landfill Leachate*", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, pp. 682-693, Vol. 131, No. 6.

Sengupta, S. and Miller, H. [2004]. "*An Evaluation of Recycled Tire Shreds as a Substitute for Gravel in Residential Soil Absorption Systems*", Civil Engineering Practice, Journal of the Boston Society of Civil Engineers Section, Vol. 19, No. 1.

Sengupta, S. and Miller, H.J. [1999]. "*Preliminary Investigation of Tire Shreds for Use in Residential Subsurface Leaching Field Systems*", Technical Report #12, Chelsea Center for Recycling and Economic Development, Technical Research Program, University of Massachusetts – Lowell, Chelsea, Massachusetts.

Sengupta, S. and Miller, H.J. [2000]. "*Investigation of Tire Shreds for Use in Residential Subsurface Leaching Field Systems: A Field Scale Study,*" Technical Report #32, Chelsea Center for Recycling and Economic Development, Technical Research Program, University of Massachusetts – Lowell, Chelsea, Massachusetts.

Shao, J., Zarling, J.P., and Esch, D. [1995]. "*Thermal Conductivity of Recycled Tire Rubber for Insulation Beneath Roadways*", Transportation Research Board, 70 pp.

Sharma, H.D. and Lewis, S.P. [1994]. "*Waste Containment Systems, Waste Stabilization, and Landfills*", Wiley and Sons, Inc., New York, New York.

Spagnoli, J.S., Weber, A.S. and Zicari, L.P. [2001]. *The Use of Tire Chips in Septic System Leachfields*, prepared for the Environmental Management Investment Group, Empire State Development, Albany, New York.

State of Maryland. [2007], *Scrap Tire Program home page*, Maryland Department of The Environment.(http://www.mde.state.md.us/Programs/LandPrograms/Solid_Waste/ScrapTire/index.asp).

Tatsiloz, N., Edil, T.B., Benson, C.H., Park, J.K., and Kim, J.Y. [1996]. "*Review of Environmental Suitability of Scrap Tires*", Environmental Geotechnics Report No. 96-7, Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Wisconsin.

Tchobanoglous, G., Theisen, H., and Vigil, S. [1993]. "*Integrated Solid Waste Management: Engineering Principles and Management Issues*", McGraw-Hill, Inc., New York.

TDCA [2005]. "*Policy Guidelines for Civil Engineering Applications Approved for Beneficial End Use of Waste Tire*", Tennessee Division of Community Assistance, http://www.state.tn.us/environment/swm/tires/tireuse.php.

Thiel, R.S. [1998]. "*Design methodology for a gas pressure relief layer below a geomembrane landfill cover to improve slope stability*", Geosynthetics International, Vol. 5, No. 6, pp. 589-617.

Tweedie, J.J., Humphrey, D.N., and Sandford, T.C. [1998a]. "*Tire Chips as Lightweight Backfill for Retaining Walls – Phase II*", University of Maine, Orono, Maine, prepared for The New England Transportation Consortium, p. 314.

Tweedie, J.J., Humphrey, D.N., and Sandford, T.C. [1998b]. "*Full Scale Field Trials of Tire Shreds as Lightweight Retaining Wall Backfill, At-Rest Condition*", Transportation Research Board, Washington, D.C.

Twin City Testing [1990]. *"Environmental Study of the Use of Shredded Waste Tires for Roadway Sub-grade Support"*. Twin City Testing Corp., St. Paul, MN, for Waste Tire Management Unit, Site Response Section, Groundwater and Solid Waste Division, Minnesota Pollution Control Agency, St. Paul, Minnesota.

USDOT [2002]. "*User Guidelines for Waste and By-Product Materials Use in Pavement Construction*", Office of Engineering Research and Development, Turner Fairbank Highway Research Center May 2002. (http://www.tfhrc.gov//hnr20/recycle/waste/intro.htm).

USEPA [1999]. "State Scrap Tire Programs, A Quick Reference Guide: 1999 Update". (http://www.epa.gov/epaoswer/non-hw/muncpl/tires/scrapti.pdf)

Wartman, J., Natale, M.F., and Strenk, P.M. [2007]. "*Immediate and Time-Dependent Compression of Tire Derived Aggregate*", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 133, No. 3.

Weber, A.S. and Kim, S. [2002]. *Hydraulic Evaluation of Chipped Tires versus natural Aggregate in a Full Scale Leachfield*, prepared for the Environmental Management Investment Group, Empire State Development, Albany, New York.

Wolfe, S.L., Humphrey, D.N., and Wetzel, E.A. [2004]. *"Development of Tire Shred Underlayment to Reduce Groundborne Vibration from LRT Track"*, Geotechnical Engineering for Transportation Projects: Proceedings of Geo-Trans 2004, ASCE, pp. 750-759.

Wu, W., Benda, C., and Cauly, R. [1997]. "*Triaxial Determination of Shear Strength of Tire Chips*", Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 123, No. 5, pp. 479-482.

Zelibor, J.L. [1991]. "*Leachate from Scrap Tires: RMA TCLP Report*", Education Seminar on Scrap Tire Management, Scrap Tire Management Council, Washington, D.C.

Zornberg, J.G., Christopher, B.R., and Oosterbaan, M.D. [2002]. "*Tire Bales in Highway Applications: Feasibility and Properties Evaluation*". Report No. CDOT-DTD-R-2005-2, prepared for Colorado Department of Transportation Research Branch.

TABLES

TABLE 3.1

SUMMARY OF TDA GRADATION PROPERTIES

Product No.	**Supplier**	**Specific Gravity G_s**	**Average Size D_{50}(1) (in.)**	**Coefficient of Uniformity C_u (2)**	**Coefficient of Curvature C_v (3)**
1	Palmer Shredding, Ferrisburg, Vermont	1.11	0.87	2.08	1.08
2	Palmer Shredding, Ferrisburg, Vermont	1.08	0.32	1.83	0.96
3	Palmer Shredding, Ferrisburg, Vermont	1.27	2.05	2.07	1.08
4	F & B Enterprises, Massachusetts	1.14	0.79	1.83	1.09
5	Pine State Recycling, Maine	1.24	0.98	1.80	0.99
6	Sawyer Environment Recycling Facility, Maine	1.23	1.26	1.70	1.15

Source: Benda [1995], Humphrey et al. [1992].

Notes:

(1) D_{50} is the particle size, in inches, corresponding to the 50% of sample weight passing an equivalent sieve opening. Similar definitions exist for D_{10}, D_{30}, and D_{60}. (See ASTM C 136 [ASTM, 2008].)

(2) C_u is defined as $C_u = D_{60}/D_{10}$. A granular material having $C_u < 5$ is considered "uniform".

(3) C_v is defined as $C_v = D_{30}^2/(D_{60}\,D_{10})$. A granular material is considered to be "well-graded" if $1 < C_v < 3$ and $C_u \geq 5$.

TABLE 3.2

SUMMARY OF TDA UNIT WEIGHT TEST RESULTS

Laboratory Test				Field Compaction	
No Compaction to Light Compaction		Compacted			
Compaction Effort	**Unit Weight (lbs/ft^3)**	**Compaction Effort**	**Unit Weight (lbs/ft^3)**	**Compaction Effort**	**Unit Weight (lbs/ft^3)**
No Compaction(1)	29.1	Laboratory (50% Standard Proctor)(1)	38.3	Field compaction equipment (8)	45.6
	30.5		40.0		45.6
Loose(2)	21.3	Laboratory (60% Standard Proctor)(2)	38.7		46.8
	30.1		40.1		41.2
	30.9		38.6		41.2
Loose(3)	25.5		39.0		41.8
Loose(4)	31.2		40.0		41.8
No Compaction -Vibratory(1)	31.0	Laboratory (Standard Proctor)(1)	39.6		43.7
	29.5		40.3		41.2
			40.8		47.4
			39.5		43.1
		Laboratory (Standard Proctor)(5)	37.1		43.7
			35.0		42.5
		Laboratory (Modified Proctor)(1)	41.7		48.1
			42.8		45.0
		Laboratory (Modified Proctor)(3)	41.2		
		Laboratory (unknown)(6)	43.2		
			43.5		
			43.6		
		Laboratory (AASHTO T 99)(7)	37.5		
			35.8		
			31.5		
			37.4		
			33.3		

Source:

1. Ahmed, 1993
2. Humphrey et al., 1992
3. Humphrey and Manion, 1992
4. Newcomb and Drescher, 1994
5. Edil and Boscher, 1992
6. Chu, 1998
7. Benda, 1995
8. Tweedie et al., 1998

TABLE 3.3

SUMMARY OF COMPRESSIBILITY PARAMETERS

No.	C_e	C_c	P_c (psf)	Sample Preparation	Test Condition	Reference
1	0.05	0.42	200	Compacted 60% STD	Side wall considered	Manion and Humphrey [1992]
2	0.08	0.38	200	Compacted 60% STD	Side wall considered	Manion and Humphrey [1992]
3	0.06	0.35	250	Compacted 60% STD	Side wall considered	Humphrey et al. [1992]
4	0.11	0.33	220	Compacted 60% STD	Side wall considered	Humphrey et al. [1992]
5	0.04	0.43	250	Compacted 60% STD	Side wall considered	Humphrey et al. [1992]
6	0.08	0.37	320	Compacted 60% STD	Side wall considered	Humphrey et al. [1992]
7	0.04	0.35	250	Compacted 60% STD	Side wall considered	Manion and Humphrey [1992]
8	0.07	0.37	200	Compacted 60% STD	Side wall considered	Manion and Humphrey [1992]
9	0.03	0.37	350	Compacted		Ahmed [1993]
10	0.04	0.35	280	Compacted		Ahmed [1993]
11	N/A	0.27	N/A	Compacted 60% STD	Side wall considered	Nickels [1995]
12	N/A	0.35	N/A	Compacted 60% STD	Side wall considered	Nickels [1995]
13	N/A	0.50	N/A	Compacted		Geosyntec [2004]
14	N/A	0.54	N/A	Compacted		Geosyntec [2004]
15	N/A	0.38	N/A	Compacted		Geosyntec [1997]
16	N/A	0.40	N/A	Compacted		Geosyntec [1997]
17	N/A	0.42	N/A	Compacted		Geosyntec [1997]
18	0.09	0.44	420	Loose		Drescher and Newcomb [1994]
19	N/A	0.51	N/A	Loose		Drescher and Newcomb [1994]
20	0.05	0.41	382	Compacted	Side wall considered	Drescher, Newcomb, Heidlamn [1999]
21	0.05	0.49	600	Compacted	Side wall considered	Bernal, Lovell [1996]
22	N/A	0.35	N/A	Loose		Edil Boscher [1994]
Average	**0.06**	**0.40**	**302**			

TABLE 3.4

SUMMARY OF TDA ELASTIC PARAMETERS

Supplier	Test No.	K_o	μ	*D* (psi)	*E* (psi)
Pine State Recycling	1	0.55	0.35	194	120
	2	0.33	0.25	245	205
	3	0.34	0.25	202	168
	Average	0.41	0.28	215	165
Palmer Shredding	1	0.29	0.22	115	102
	2	-	-	364	-
	3	0.22	0.18	252	222
	Average	0.26	0.20	244	161
F&B Enterprises	1	0.40	0.29	151	70
	2	0.55	0.36	180	107
	3	0.45	0.31	220	160
	Average	0.47	0.32	184	112
Sawyer Environmental	1	0.33	0.25	263	219
	2	0.65	0.39	293	146
	3	0.40	0.29	222	170
	4	0.45	0.31	228	164
	5	0.35	0.26	249	205
	Average	0.44	0.30	251	181

After Humphrey et al. [1992].

TABLE 3.5

SUMMARY OF SHEAR STRENGTH PARAMETERS OBTAINED FROM DIRECT SHEAR TESTS

Displacement (in.)	σ < 10 psi	σ > 10 psi	
	ϕ_1 (degrees)	ϕ_2 (degrees)	c_2 (psi)
0.5	24.0	15.6	1.7
1.0	30.8	21.7	2.0
1.5	35.2	24.8	2.4
2.0	39.2	27.8	2.9

TABLE 3.6

SUMMARY OF SHEAR STRENGTH PARAMETERS OBTAINED FROM TRIAXIAL COMPRESSION TESTS

Strain (%)	**$\sigma < 10$ psi**	**$\sigma > 10$ psi**	
	ϕ_1 (degrees)	**ϕ_2 (degrees)**	**c_2 (psi)**
5	13.9	7.9	2.2
10	22.1	13.0	3.5
15	29.0	18.4	4.4
20	34.8	23.1	5.4

TABLE 4.1

COEFFICIENT OF INTERACTION BETWEEN TDA AND GEOSYNTHETICS (1)

Geosynthetics (2)	**Geogrid A**	**Geogrid B**	**Geogrid C**	**Geotextile**
Aperture size (in.^{2})	0.8 × 0.8	2 × 2	4 × 4	N/A
C_i	0.22–0.37	0.34–0.49	0.25–0.33	0.18–0.53

Notes:

(1) After Bernal et al. [1996].

(2) Geogrid A: FORTRAC 55/30-20, Geogrid B: FORTRAC-OM 35/35-50, Geogrid C: FORTRAC 35/35-100S manufactured by Huesker, Inc.

TABLE 5.1

TDA GRADATION RECOMMENDED FOR LANDFILL GAS COLLECTION LAYER (1)

Sieve Size in. (U.S. size)	Minimum Passing (% by weight)
12	100
6	95
3	50
0.187 (No. 4)	5

Note: (1) Based on recommendations by Geosyntec [1998b].

TABLE 5.2

TDA GRADATION RECOMMENDED FOR LANDFILL DRAINAGE LAYERS (1)

Sieve Size in. (U.S. size)	**Percent Passing (% by Weight)**
12	100
6	95
3	85
2	50
0.187 (No. 4)	5

Note: (1) Based on recommendations by Geosyntec [1998c].

TABLE 5.3

TDA GRADATION RECOMMENDED FOR LANDFILL PROTECTIVE LAYERS (1)

Sieve Size in. (U.S. size)	**Minimum Passing (% by weight)**
18	100
12	95
6	75

Note: (1) Based on recommendations by Geosyntec [1998d].

TABLE 5.4

SUMMARY OF TDA ENGINEERING PROPERTIES AND SAND USED IN FINAL COVER OF DSI LANDFILL (1)

Property	TDA	Sand
Dry Density	40	100
Moist Density	45	120
Wet Density	70	13.5
Internal Friction Angle (degrees)	27.5	35
Cohesion (psf)	80	0
Geotextile Interface Friction Angle (degrees)	34	30
Geomembrane Interface Friction Angle (degrees)	34	34
Hydraulic Conductivity (cm/s)	1	0.01

Note: (1) After Andrews and Guay [1996].

TABLE 6.1

COEFFICIENT OF AT-REST LATERAL EARTH PRESSURE (K_o) OBTAINED FROM LABORATORY AND FIELD TESTS

Supplier	Laboratory Results Average (1)	Field Result (2)	
		6.6-ft Depth	13.1-ft Depth
Pine State Recycling	0.41	0.32	0.25 – 0.26
Palmer Shredding	0.26	0.27 – 0.33	0.17 – 0.27
F&B Enterprises	0.47	0.32 – 0.33	0.25 – 0.28

Notes:

(1) Humphrey et, al. [1992].
(2) Tweedie, et al. [1998].

TABLE 6.2

LATERAL EARTH PRESSURE MEASURED ON THE MERRYMEETING BRIDGE ABUTMENT WALL (1)

Time of Reading	Elev. = 22.0 ft	Elev. = 25.5 ft	Elev. = 29.0 ft
Completion of TDA placement (psi)	1.14	0.88	0.38
Completion of soil cover and surcharge placement (psi)	2.47	2.84	2.47
24 days after completion of soil cover and surcharge placement (psi)	2.65	3.04	2.94

Note: (1) After Humphrey [1998].

TABLE 6.3

EFFECT OF COVER THICKNESS ON MAXIMUM TENSILE STRAIN AT BOTTOM OF PAVEMENT (1)

Overlying Soil Cover (in.)	Maximum Tensile Strain (ε_t) (%)	Ratio of $(\varepsilon_t)/(\varepsilon_t)_{soil}$
0	0.630	13.0
9	0.099	2.0
18	0.051	1.0
24	0.044	0.9
30	0.042	0.9
All soil	0.048	1.0

Note: (1) After Humphrey and Nickles [1997].

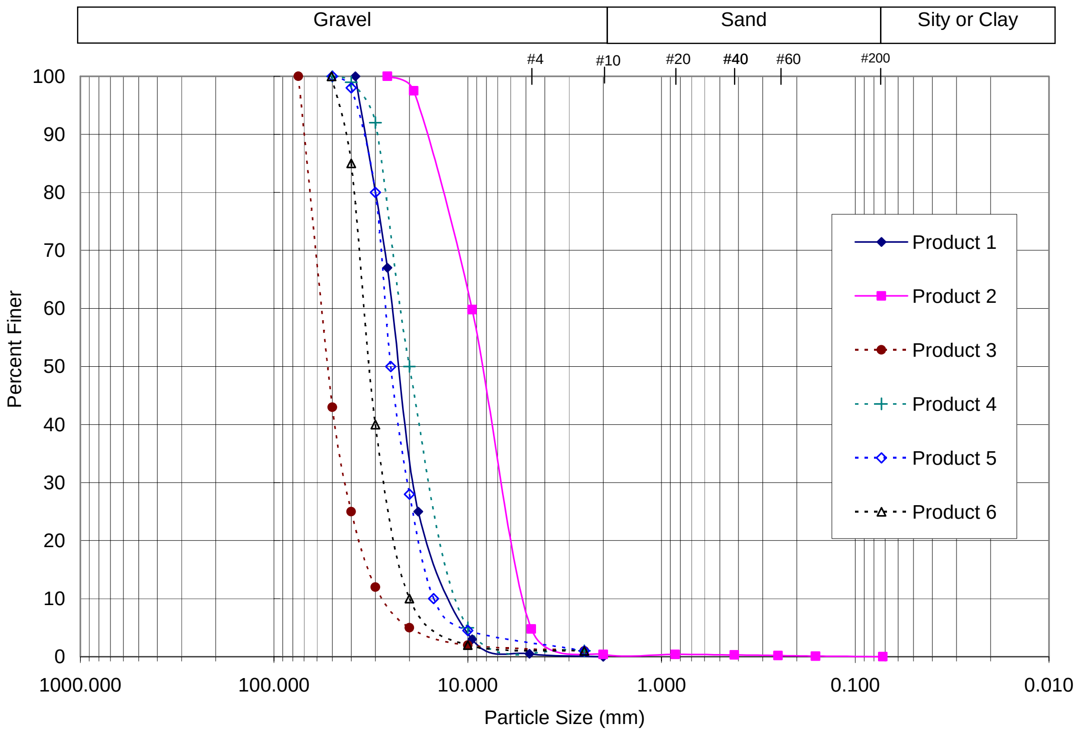
TABLE 6.4

TDA MATERIAL SPECIFICATIONS FOR SEPTIC DRAINAGE FIELD

Item	Range or Limit
TDA Size	0.5 in. to 3 in.
Presence of Wires	May not protrude more than 0.5 in. from the TDA particle edge.
Gradation	At least 90% to 95% by weight of material satisfy TDA size requirement.
Fines (< U.S. No. 200 sieve)	0% to 3.75%.

Note: Compilation of TDA guidelines for Georgia, Kansas, South Carolina, Texas, and Virginia, as outlined by Sengupta and Miller [1999].

FIGURES



Source: Benda [1995], Humphrey et al. [1992]

Note: See Table 3.1 for TDA product supplier.

Figure 3.1: Particle-Size Distribution of TDA Products

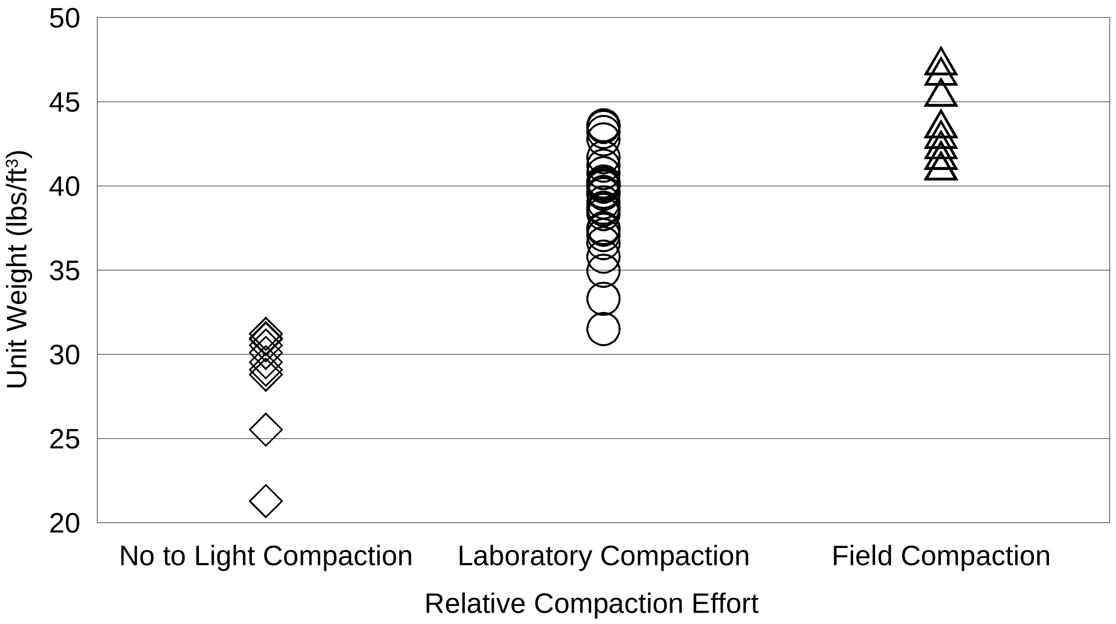


Figure 3.2: Comparison of TDA Unit Weight by Compaction Condition

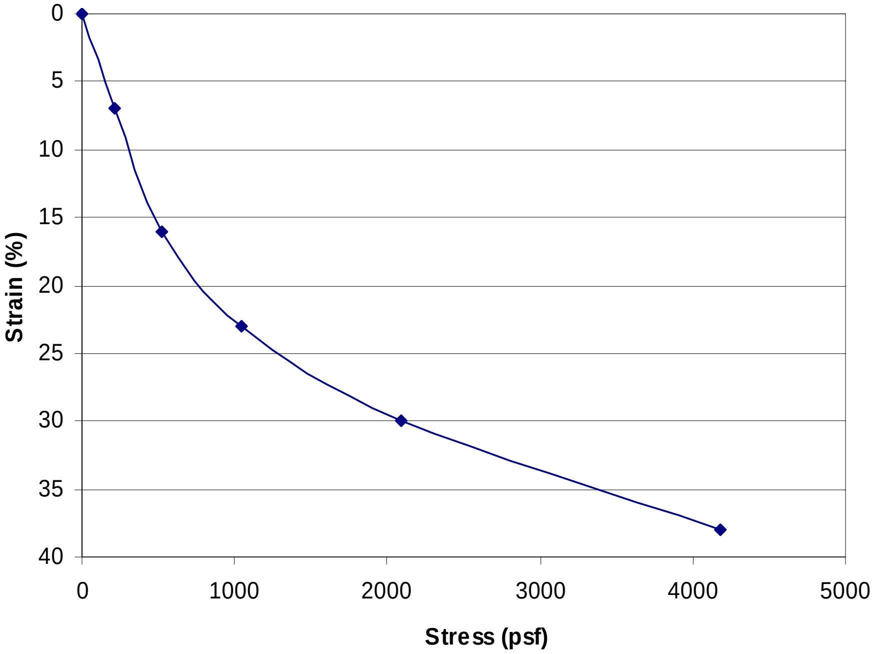


Figure 3.3: Typical Stress-Strain Curve Obtained from Constrained Compression Test (After Manion and Humphrey, 1992)

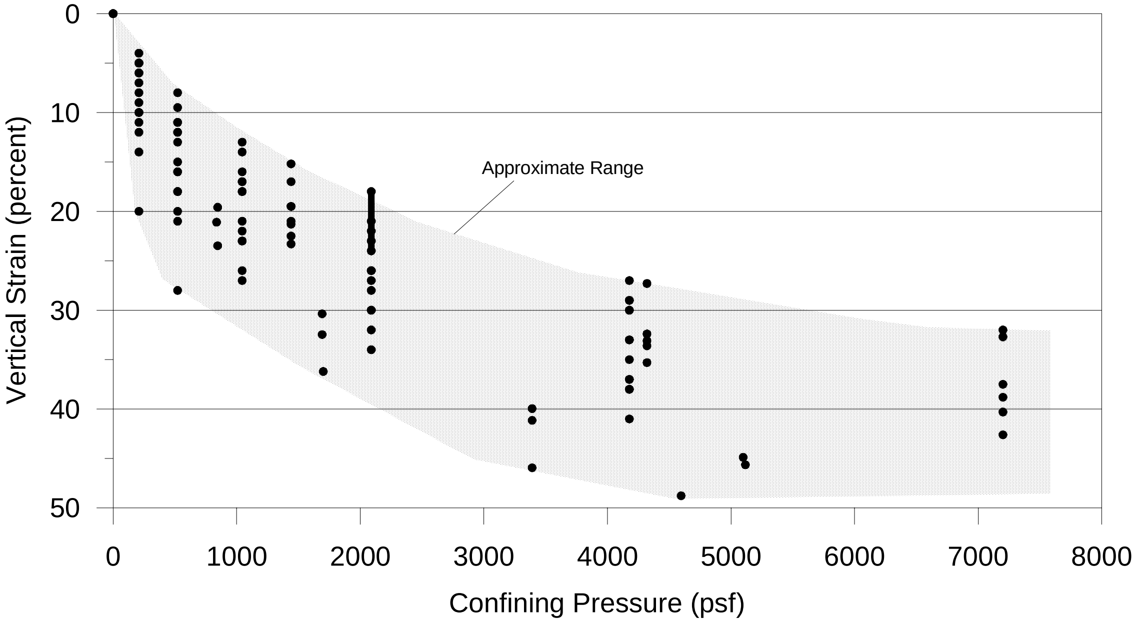


Figure 3.4: Summary of Constrained Compression Test Results

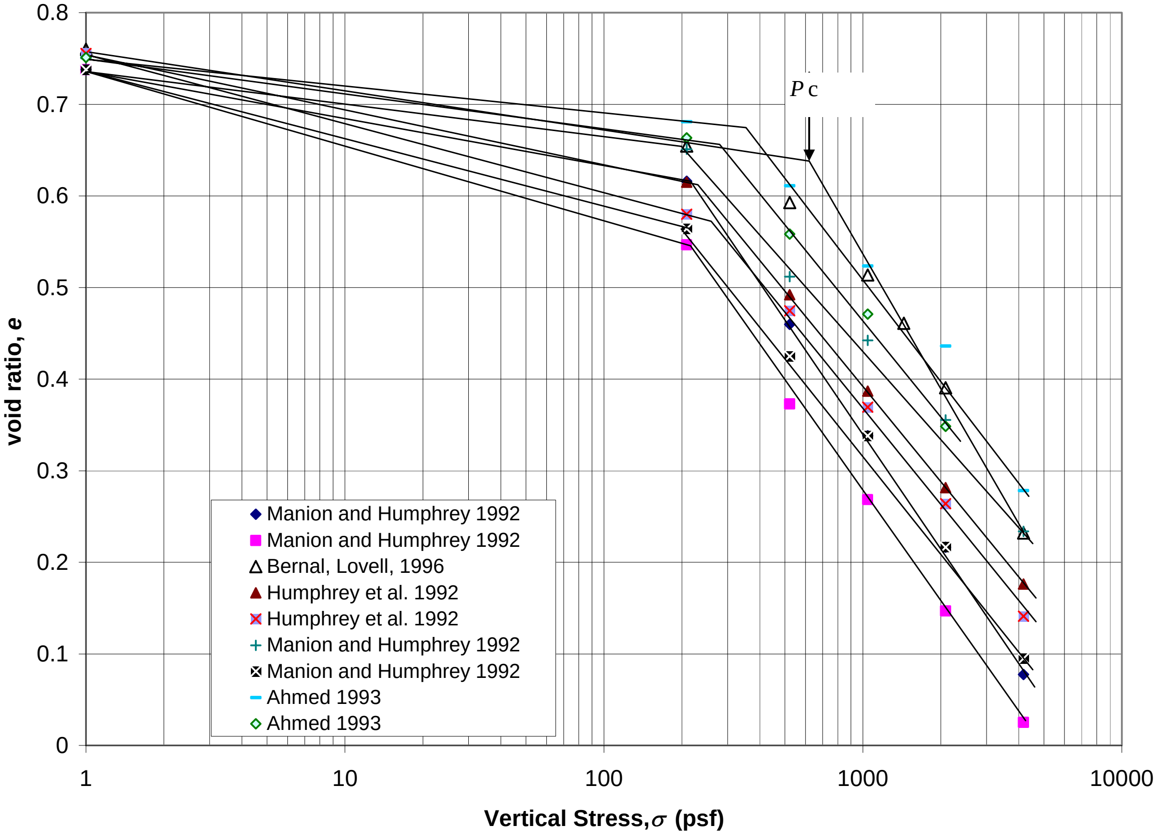


Figure 3.5: Summary of Constrained Compression Test Results (Log Scale)

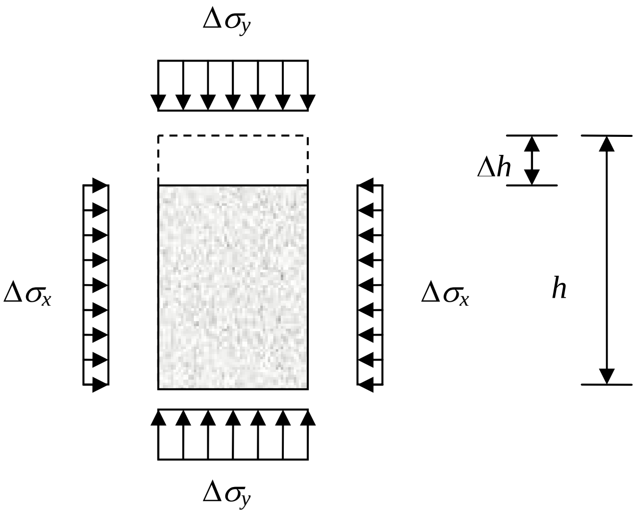


Figure 3.6: Illustration of Constrained Compression Test

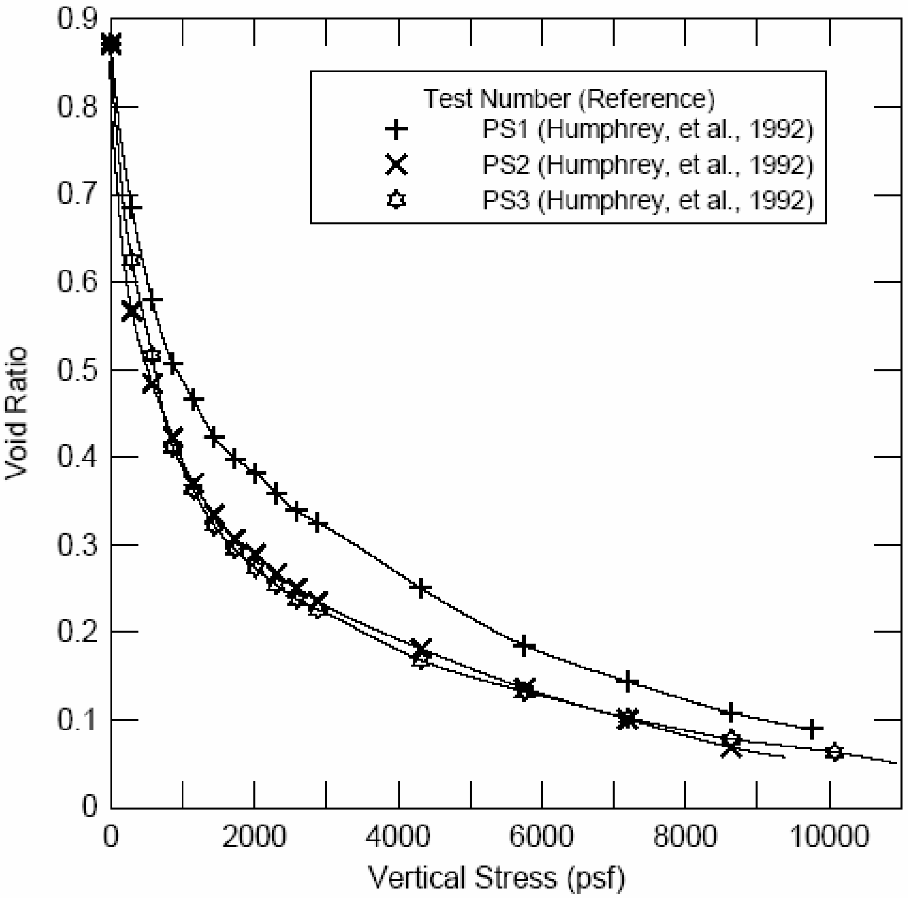
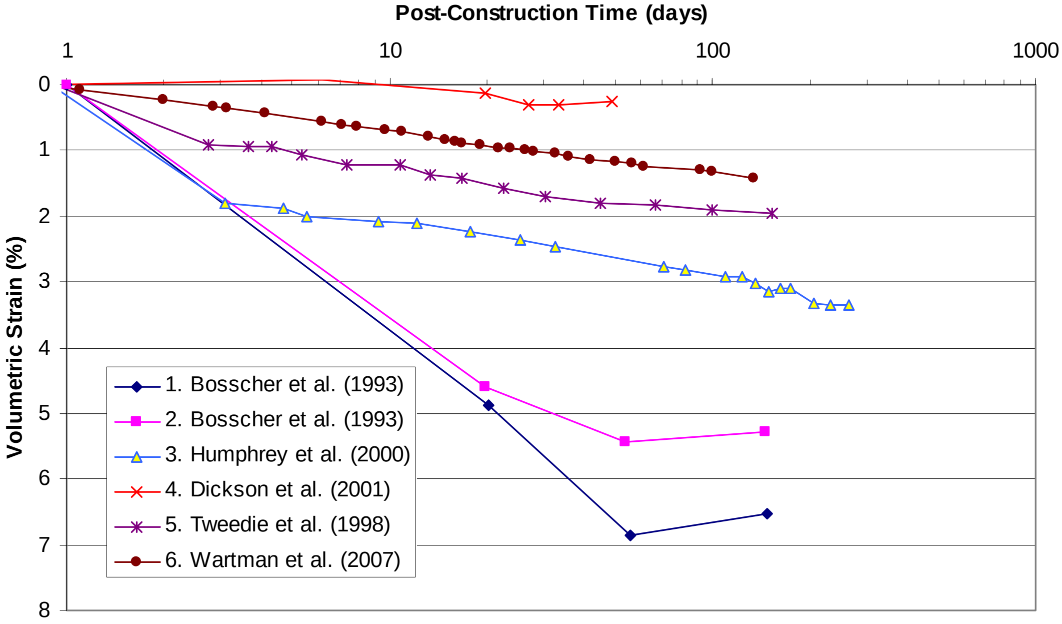


Figure 3.7: Void Ratio of TDA under Varying Vertical Stresses (Type B TDA with Maximum Size of 12 in.)



Reference	Structure Type	Max. Size (in.)	Unit Weight (pcf)	TDA Layer Thickness (ft)	Nature of Loading
1. Bosscher et al. (1993)	Roadway Embankment	1.5	32	5	Traffic
2. Bosscher et al. (1993)	Roadway Embankment	3	34	5	Traffic
3. Humphrey et al. (2000)	Bridge Abutment	12	55	14	Surcharge, Traffic
4. Dickson et al. (2001)	Roadway Embankment	12	37	10	Surcharge
5. Tweedie et al. (1998)	Retaining Wall	3	43	16	Surcharge
6. Wartman et al. (2007)	Laboratory Oedometer Test	1.2	40	0.24	Static vertical load = 1,670 psf

Figure 3.8: Summary of Results of TDA Time-Dependent Deformation

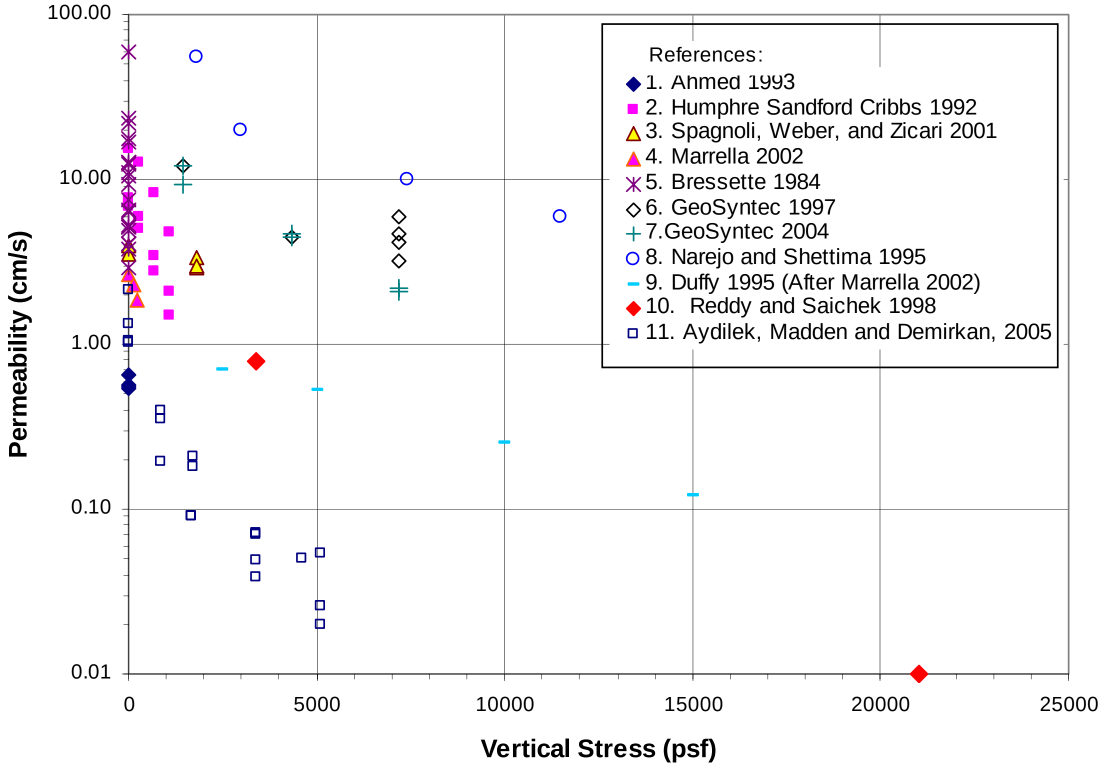


Figure 3.9: Comparison of Hydraulic Conductivity Values for TDA under Varying Vertical Stresses

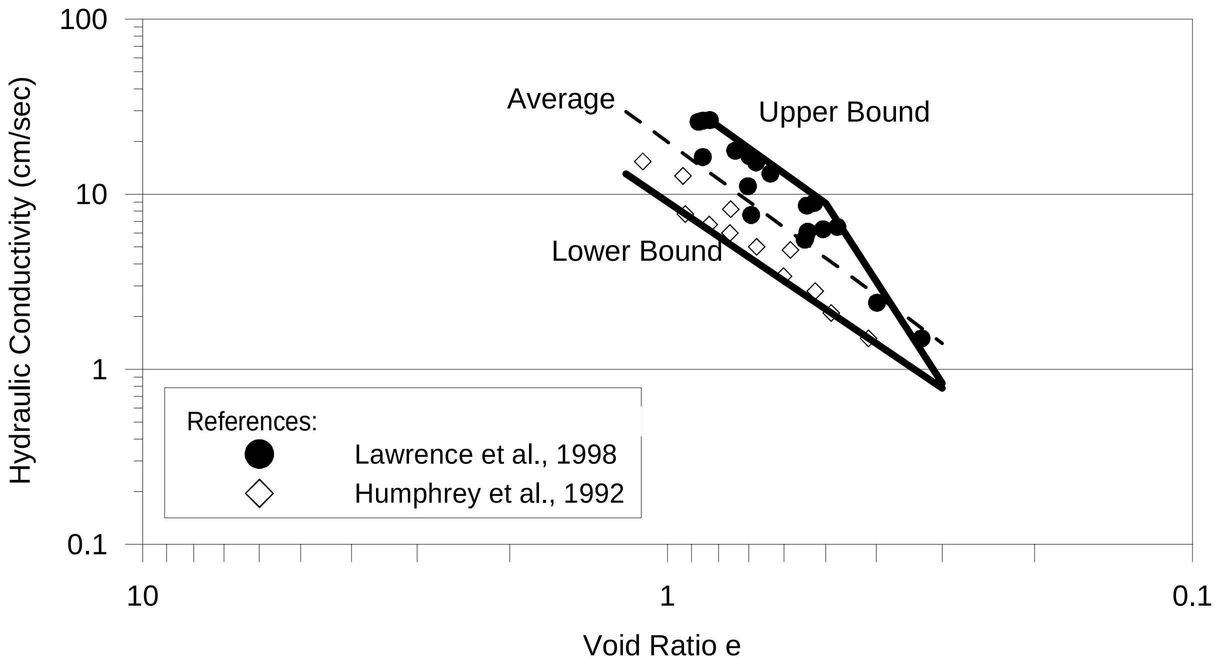


Figure 3.10: TDA Hydraulic Conductivity as a Function of Void Ratio

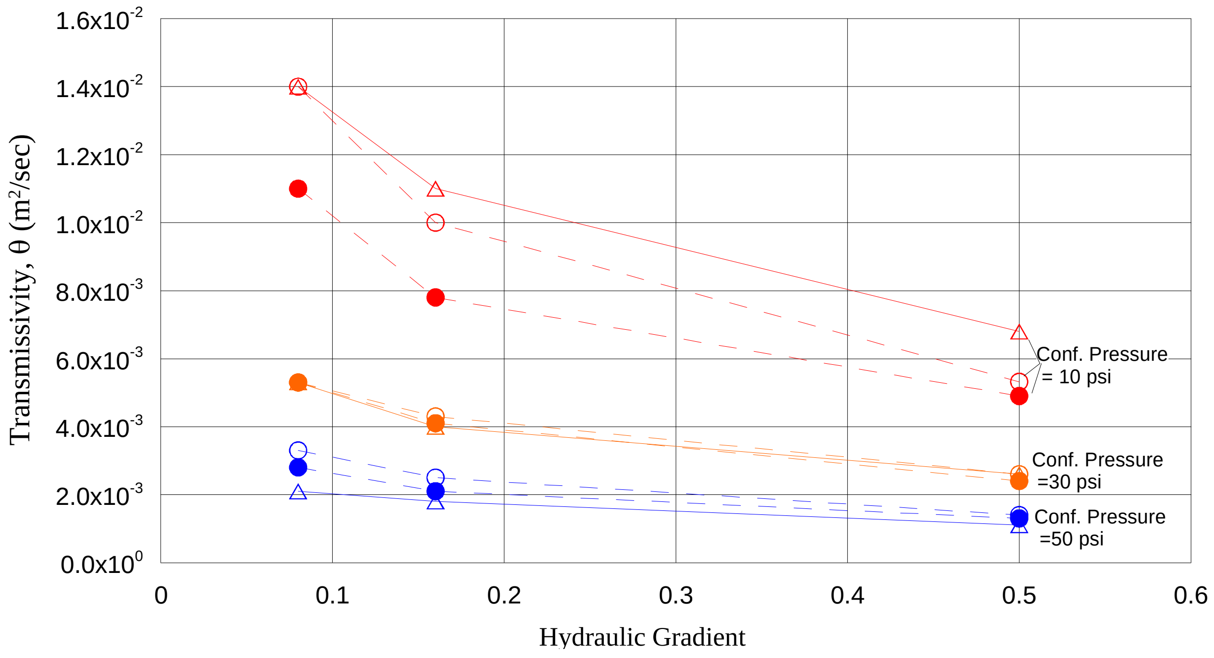
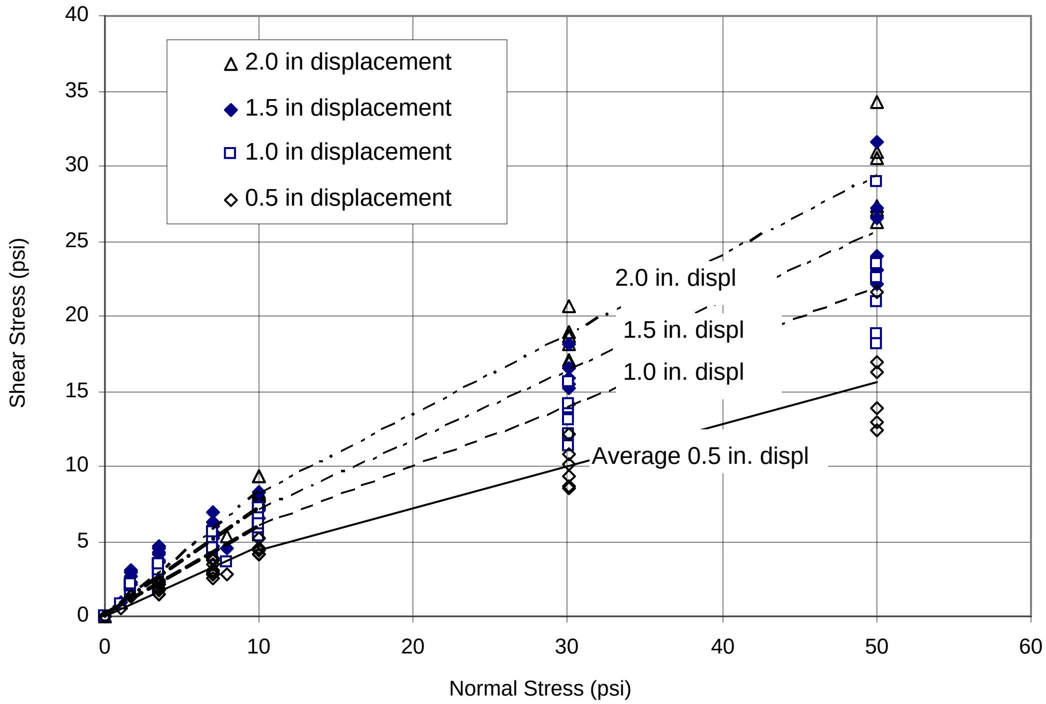
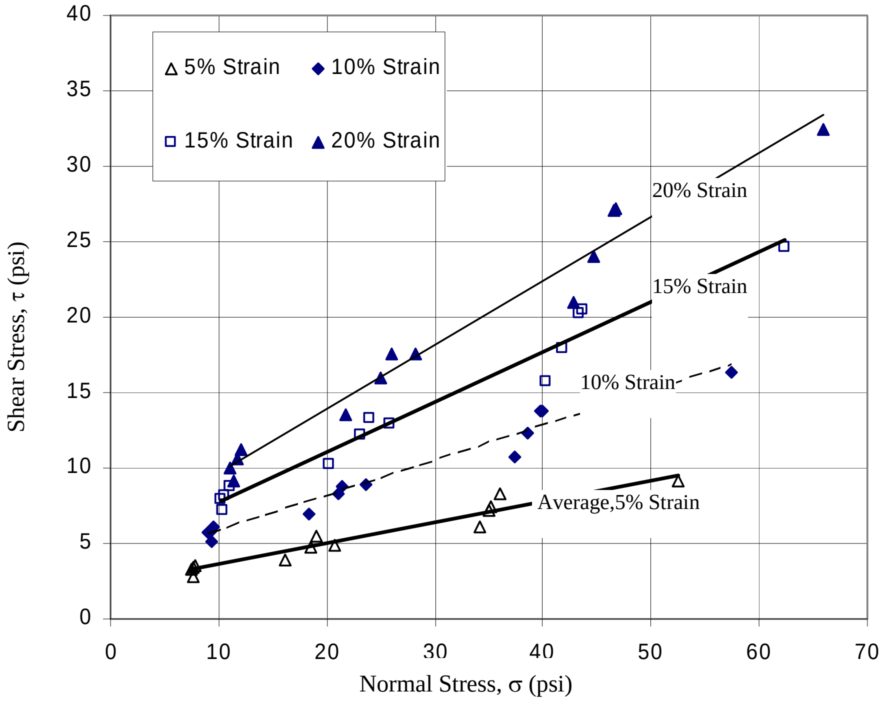


Figure 3.11: Effect of Confining Pressure and Hydraulic Gradient on Transmissivity of TDA

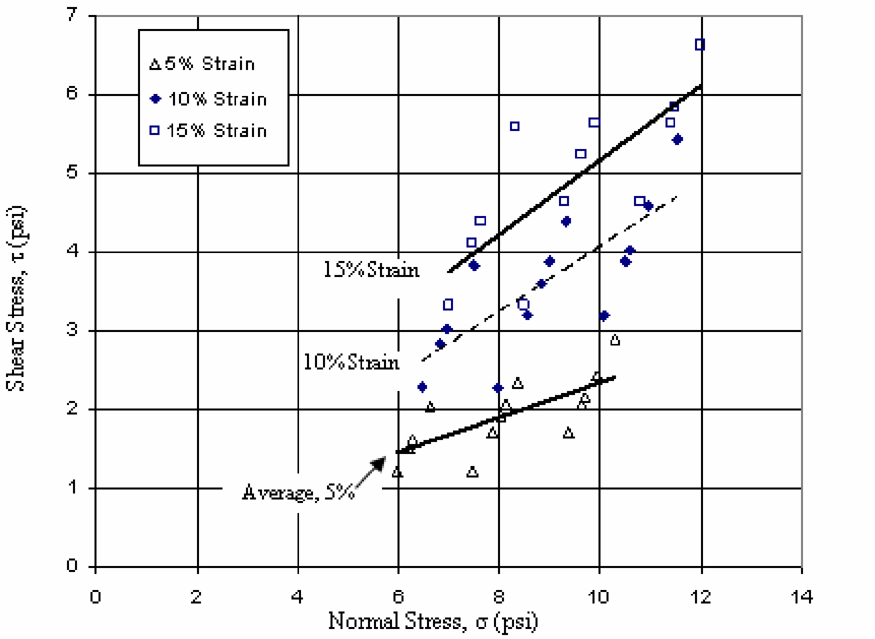


Source: Bernal, 1996; Geosyntec, 1997, 2004; Humphrey et al., 1992

Figure 3.12: Comparison of Shear Strength Envelopes Obtained from Direct Shear Tests



(a) Source: Ahmed [1993]



(b) Source: Benda [1995]

Figure 3.13: Shear Strength Results Obtained from Triaxial Compression Tests

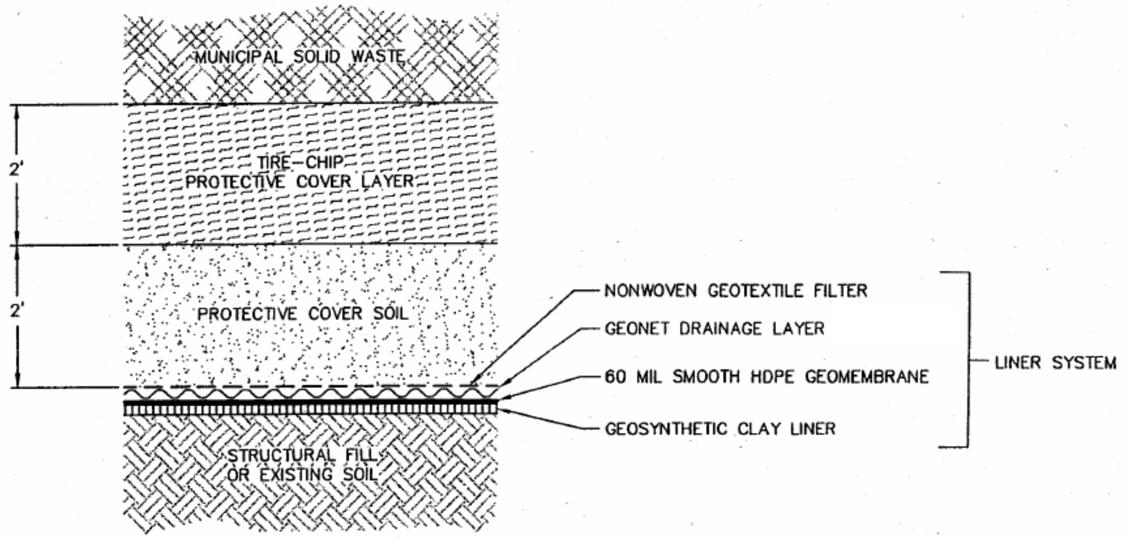
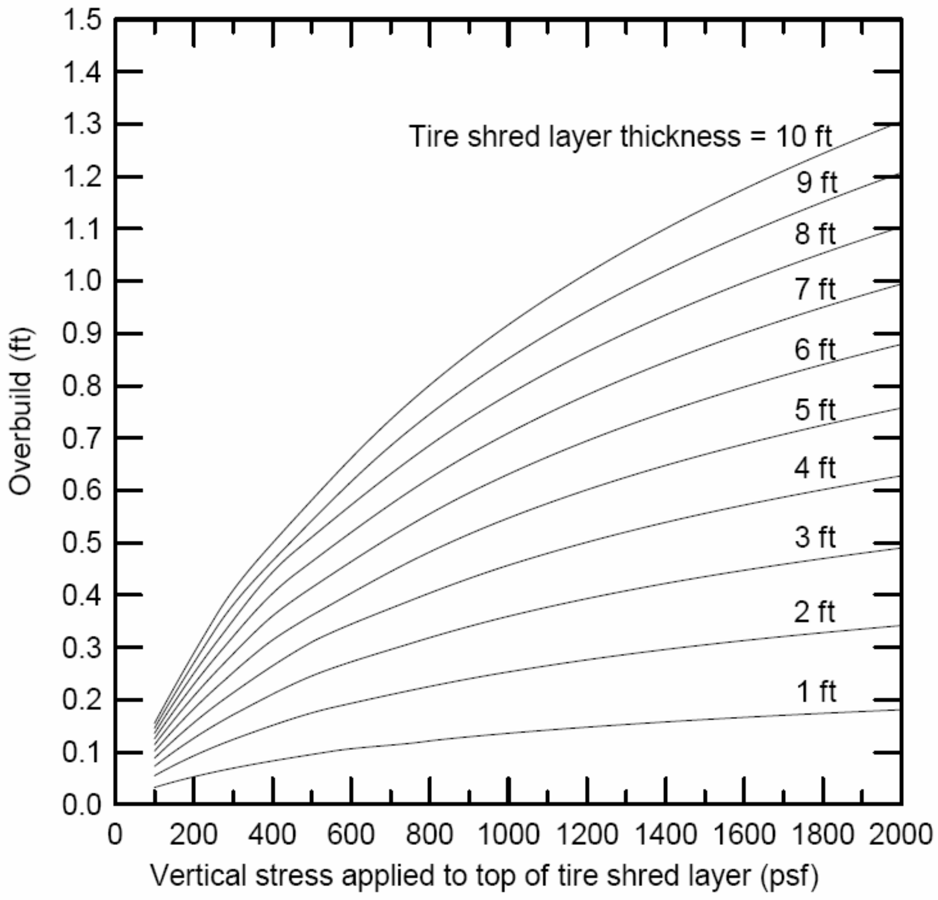
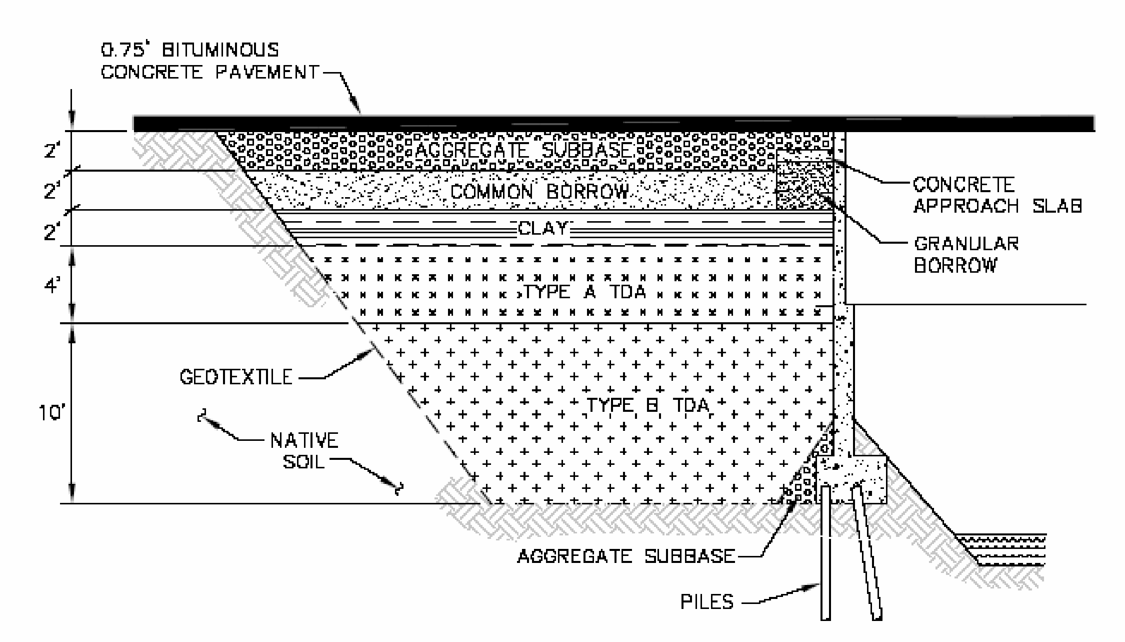


Figure 5.1: Cross-Section of Landfill Liner on Cell Floors



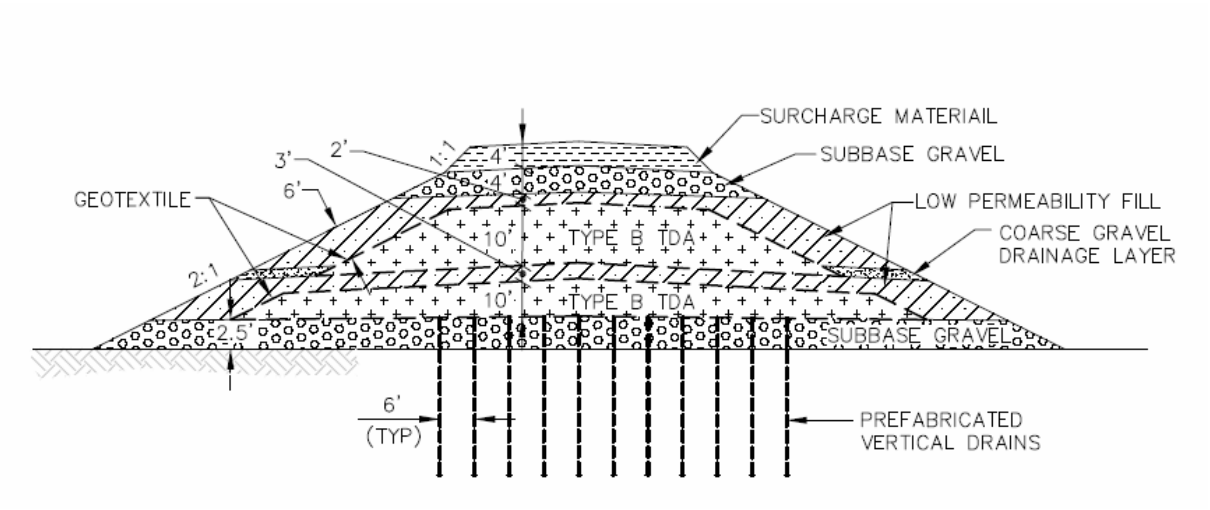
Source: Humphrey [2002]

**Figure 6.1: Overbuild Design Chart for TDA (Type B)
(Maximum Size = 12 in.)**



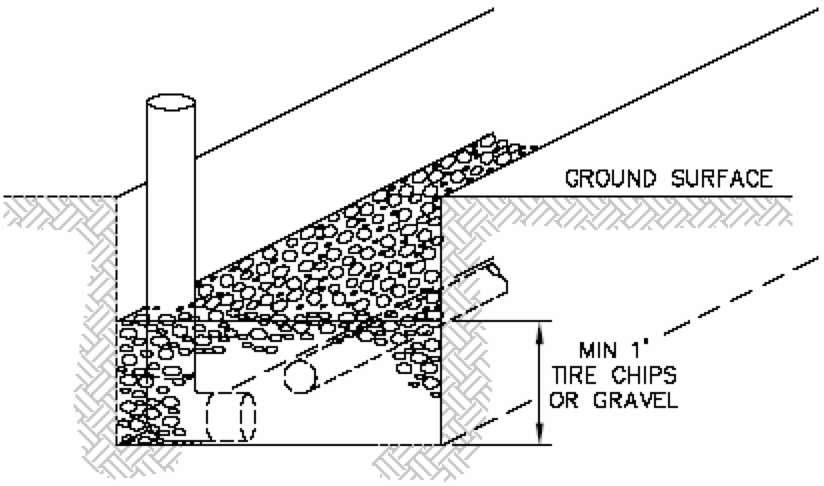
Source: Humphrey [1998]

Figure 6.2: Cross-Section of Merrymeeting Bridge Abutment, Topsham, Maine



Source: Humphrey et al. [1998]

Figure 6.3: Cross-Section of the Portland Jetport Highway Embankment



Source: Doak [2000]

Figure 6.4: Sampling Ports and Cross-Section of the Leach Trench of Colorado Demonstration Project

APPENDIX A

SUMMARY OF TEST DATA

TABLE A.1

SUMMARY OF TIRE DERIVED AGGREGATE LABORATORY COMPRESSION TEST RESULTS

Sample Preparation	Test Conditions	Stress (psf)	Strain	Stress (psf)	Strain	Stress (psf)	Strain	Stress (psf)	Strain	Stress (psf)	Strain	Stress (psf)	Strain	Stress (psf)	Strain	Reference
Compacted 60% STD	Side wall considered	209	7	522	16	1,044	23	--	--	2,089	30	4,177	38	--	--	1
Compacted 60% STD	Side wall considered	209	11	522	21	1,044	27	--	--	2,089	34	4,177	41	--	--	1
Compacted 60% STD	Side wall considered	209	8	522	15	1,044	21	--	--	2,089	27	4,177	33	--	--	2
Compacted 60% STD	Side wall considered	209	14	522	20	1,044	26	--	--	2,089	32	4,177	37	--	--	2
Compacted 60% STD	Side wall considered	209	5	522	11	1,044	18	--	--	2,089	26	4,177	33	--	--	2
Compacted 60% STD	Side wall considered	209	10	522	16	1,044	22	--	--	2,089	28	4,177	35	--	--	2
Compacted 60% STD	Side wall considered	209	5	522	13	1,044	17	--	--	2,089	22	4,177	29	--	--	3
Compacted 60% STD	Side wall considered	209	10	522	18	1,044	23	--	--	2,089	30	4,177	37	--	--	3
Compacted	Side wall not considered	209	4	522	8	1,044	13	--	--	2,089	18	4,177	27	--	--	4
Compacted	Side wall not considered	209	5	522	11	1,044	16	--	--	2,089	23	--	--	--	--	4
Compacted 60% STD	Side wall considered	209	12	522	18	--	--	--	--	--	--	--	--	--	--	5
Compacted 60% STD	Side wall considered	209	20	522	28	--	--	--	--	--	--	--	--	--	--	5
Compacted	Side wall not considered	--	--	--	--	1,440	22.5	1,440	22.5	--	--	4,320	33.6	7,200	40.3	6
Compacted	Side wall not considered	--	--	--	--	1,440	23.3	1,440	23.3	--	--	4,320	35.3	7,200	42.6	6
Compacted	Side wall not considered	--	--	--	--	1,440	21.3	1,440	21.3	--	--	4,320	32.4	7,200	37.5	7
Compacted	Side wall not considered	--	--	--	--	1,440	15.2	1,440	15.2	--	--	4,320	27.3	7,200	32.7	7
Compacted	Side wall not considered	--	--	--	--	1,440	21	1,440	21	--	--	4,320	33.1	7,200	38.8	7
Loose	Side wall not considered	209	9	522	12	1,044	17	--	--	2,089	24	4,177	30	--	--	8
Loose	Side wall not considered	--	--	522	17	1,044	24	--	--	2,089	31	4,177	38	--	--	8
Compacted	Side wall considered	209	6	522	12	1,044	18	--	--	2,089	26	--	--	--	--	9
	Sidewall lubed	--	--	--	--	--	--	--	--	2,506	26	--	--	--	--	10
Compacted	Side wall considered	209	6	522	9.5	1,044	14	1,440	17	2,089	21	4,177	30	--	--	11
Loose	Side wall not considered	--	--	418	7	1,044	18	1,440	19.5	2,089	23.5	4,177	29	7,200	32	12
Loose	Side wall lubed	--	--	--	--	850	23.5	--	--	1,700	36.2	3,390	45.9	4,596	48.8	13
Loose	Side wall lubed	--	--	--	--	850	21.1	--	--	1,700	32.5	3,390	41.1	5,116	45.6	13
Loose	Side wall lubed	--	--	--	--	850	19.6	--	--	1,700	30.7	3,390	40	5,098	44.9	13

References:

1. Manion and Humphrey [1992]
2. Humphrey et al. [1992]
3. Manion and Humphrey [1992]
4. Ahmed [1993]
5. Nickels [1995]
6. Geosyntec [2004]
7. Geosyntec [1997]
8. Drescher and Newcomb [1994]
9. Drescher Newcomb Heidlamn [1999]
10. Tatlisoz [1997]
11. Bernal, Lovell [1996]
12. Edil Boscher [1994]
13. Aydilek et al. [2005]

TABLE A.2

SUMMARY OF TIRE DERIVED AGGREGATE LABORATORY PERMEABILITY TEST RESULTS ACCORDING TO TEST PRESSURE

Confining Pressure (psf)	Permeability (cm/sec)	Reference	Confining Pressure (psf)	Permeability (cm/sec)	Reference	Confining Pressure (psf)	Permeability (cm/sec)	Reference	Confining Pressure (psf)	Permeability (cm/sec)	Reference
0-1, 100	0.6	1	0-1, 100	5.1	7	0-1, 100	6.1	3	1,100-4,400	4.5	8
	0.6	1		3.8	7		11.1	3		4.7	9
	0.6	1		4.1	7		17.7	3		4.5	9
	0.5	1		6.4	7		13.1	3		2.4	3
	1.9	2		17.7	7		16.5	3		5.5	3
	2.6	2		10.4	7		15.2	3		5.6	3
	1.2	2		22.0	7		6.0	4		8.6	3
	2.6	2		7.5	7		12.7	4		8.9	3
	2.7	2		23.5	7		5.0	4		3.4	4
	7.6	3		5.3	7	1,100-4,400	3.0	4		8.2	4
	16.3	3		12.7	7		2.8	4		2.8	4
	25.9	3		6.6	7		0.8	2	4,400-10,000	0.5	11
	26.3	3		12.8	7		2.2	2		2.2	8
	26.5	3		4.9	7		2.6	2		2.1	9
	7.7	4		59.3	7		1.4	2		2.2	9
	15.4	4		12.3	7		12.1	8		10.0	10
	6.7	4		16.8	7		9.4	9		0.3	11
	3.5	5		2.3	6		12.1	9		1.5	3
	4.0	5		1.8	6		1.9	2		6.3	3
	2.6	6		3.0	5		55.0	10		6.5	3
	5.1	7		3.4	5		2.6	4		2.1	4
	10.9	7		2.9	5		2.4	4		4.8	4
	2.9	7		3.0	5		0.7	11		1.5	4
	9.3	7		2.5	2		20.0	10	>10,000	6.0	10
	4.1	7		1.6	2		0.8	12		0.1	11
										0.0	12

References

1. Ahmed, 1993
2. Hall, 1991
3. Lawrence et al., 1998
4. Humphrey et al., 1992
5. Spagnoli et al., 2001
6. Marella, 2002
7. Bressette, 1984
8. Geosyntec, 1997
9. Geosyntec, 2004
10. Narejo et al., 1995
11. Duffy, 1995 (after Marella, 2002)
12. Reddy et al., 1998

TABLE A.3

SUMMARY OF TIRE DERIVED AGGREGATE LABORATORY PERMEABILITY TEST RESULTS ACCORDING TO VOID RATIO

Void Ratio	Permeability cm/sec	Reference
0.693	7.6	1
0.857	16.3	1
0.873	25.9	1
0.856	26.3	1
0.831	26.5	1
0.541	6.1	1
0.703	11.1	1
0.743	17.7	1
0.637	13.1	1
0.699	16.5	1
0.678	15.2	1
0.399	2.4	1
0.548	5.5	1
0.546	5.6	1
0.543	8.6	1
0.526	8.9	1
0.328	1.5	1
0.506	6.3	1
0.475	6.5	1
0.925	7.7	2
1.114	15.4	2
0.833	6.7	2
0.761	6.0	2
0.935	12.7	2
0.676	5.0	2
0.601	3.4	2
0.758	8.2	2
0.523	2.8	2
0.488	2.1	2
0.583	4.8	2
0.414	1.5	2

References

1. Lawrence et al., 1998
2. Humphrey et al., 1992

TABLE A.4

SUMMARY OF TIRE DERIVED AGGREGATE SHEAR STRENGTHS LABORATORY TEST RESULTS

Test Method	Range of Testing Normal Stress (lbs/ft^2)	Failure Criterion	Calculated Friction Angle (degree)	Cohesion Intercept (lbs/ft^2)
Triaxial (1)	720 – 1,152	e = 10%	21.1	0
			21.4	0
			17.2	0
			20.6	0
Direct Shear (2)	42 – 125	e = 10%	38	69
			32	90
Direct Shear (3)	144 – 1,138	e = 10%	24	0
Direct Shear (4)	360 – 1,300	e = 10%	25	180
			19	240
			21	160
			26	90
Direct Shear (5)	1,440 – 7,200	e = 8%	20	390
			23	300
			28	145
			22	230
Direct Shear (6)	1,440 – 7,200	e = 8%	18	305
			18	380

References

1. Benda, 1995
2. Cosgrove, 1995
3. Bernal, 1995
4. Humphrey, 1992
5. Geosyntec, 1997
6. Geosyntec, 2002

APPENDIX B

LIST OF SPECIALTY LABORATORIES

APPENDIX B

SPECIALTY LABORATORIES FOR TDA TESTING

Labs	Contact Information	Types of Tests Performed
TRI/Environmental	ATTN: Geosynthetics Services 9063 Bee Caves Road Austin, Texas 78733 Tel: (512) 263-2101 Toll free: (800) 880-8378 Fax: (512) 263-2558 Email: Sallen@tri-env.com	Transmissivity, permeability, compression strength, shear strength, and interface strength
SGI Testing	4405 International Boulevard Suite-B117 Norcross, Georgia 30093 Toll Free: 1-866-SGI-LAB1 Vox: 770-931-8222 Fax: 770-931-8240	Transmissivity, permeability, compression strength, shear strength, and interface strength
Precision Geosynthetic Laboratories	1160 North Gilbert Street Anaheim, California 92801 Tel: 714-520-9631 Fax: 714-520-9637	Transmissivity, permeability, compression strength, shear strength, and interface strength

APPENDIX C

MANUFACTURERS AND VENDORS OF RECYCLED RUBBER PRODUCTS

APPENDIX C

MANUFACTURERS AND VENDORS OF RECYCLED RUBBER PRODUCTS

Advanced Polymer Technology
Harmony, Pennsylvania
Tel: (724) 452-1330
- Makes sports and recreational surfacing systems.

Advanced Rubber Surfacing Products
Red Bluff, California
Tel: (530) 527-5272
- Manufacture playground mats from recycled rubber.

Aquapore Moisture Systems, Inc.
Phoenix, Arizona
Tel: (800) 635-8379
- Manufacture underground and above ground soaker and sprinkler hoses made of 65% scrap tire material for residential and commercial use.

Artistic Office Products
Port Morris, New York
Tel: (718) 665-5510
- Manufacture and sales of recycled-content office products.

Ashland Rubber Mat Co., Inc.
Ashland, Ohio
Tel: (419) 6289-7614
- Manufacture doormats.

Auston Tire Recycling Facility
Joppa, Maryland
Tel: (410) 335-1016
- Scrap Tire Recycler.

Belting Associates, Inc.
Hicksville, New York
Tel: (516) 433-2828
- Distribute a line of entrance mats and floor tiles that contain recycled tire rubber.

Beasley Tire Recycling
Lynchburg, Virginia
Tel: (434) 665-1436
- Scrap tire disposal; TDA provider.

Buffalo Polymer Processors, Inc.
Holland, New York
Tel: (716) 537-3153
- Manufacture interlocking floor tiles and imitation slate roofing tile.

CB Worldwide, Inc.
Mammoth Lakes, California
Tel: (760) 934-8677
Web: www.mammothpet.com
- Manufacture pet toys and die-cut tire parts from recycled tires.

Child Safe Products
645 Broadway
Amityville, New York 11801
Tel: (800) 434-5616
Web: www.childsafeproducts.com
- Poured in-place rubber mats.

Continental Turf Systems
Continental, Ohio
Tel: (419) 596-4242
Web: www.continentalturf.com
- Tire Turf recycled rubber ground cover, playground surfacing, horse arenas and landscape.

Direct Access
Lake Park, Florida
Tel: (800) 811-7383
Web: www.directaccessintl.com
- Distribute products such as jar openers, coasters, notebooks, and mouse pads made from recycled rubber.

Duroplas Corporation
101 Peninsula Drive
North East, Maryland 21901
Web: www.Duroplas.com
Email: leroycox@duroplas.com and lisasniadach@duroplas.com
- Develop thermoplastic elastomer compound products used in standard commercial molding applications that contain up to 75% post consumer and/or post industrial recycled raw materials.

D&J Farms
Northbridge, Massachusetts
Tel: (508) 234-8197
- Make mats for cow trailers and horse arenas from scrap tire buffings.

Emanuel Tire Company
Baltimore, Maryland
Tel: (410) 947-0725
Web: http://www.emanueltire.com/
- Waste tire disposal; Manufacture TDA, rubber mulch, tire derived fuel, playground cover, sound wall material, rubber reclaim industry material.

Emanuel Tire of Virginia
Waverly, Virginia; Appomattox, Virginia
Tel: (804) 834-1130 (Waverly); (434) 352-8889 (Appomattox)
- Waste tire disposal; Manufacture TDA, rubber crumb.

Global Rubber, Inc.
King of Prussia, Pennsylvania
Tel: (610) 878-9200
Web: http://hometown.aol.com/grtsales/4.htm
- Manufacture mats (livestock, athletic, etc.), roofing, traffic control devices, etc.

Great Outdoors Sales & Service
Elkridge, Maryland
Tel: (410) 379-0767
- Distribute line of recycled rubber mats for recreational use, gym/exercise, and golf cart paths.

Green Earth Office Supply
Redwood Estates, California
Tel: (800) 327-8449
Web: www.greenearthofficesupply.com
- Distributor of office and school supplies including recycled rubber pens, mouse pads, briefcases.

John Rossi Company, Inc.
Briarcliff, New York
Tel: (914) 941-1752
- Product design and development of upscale stationary products with recycling materials.

Keystone Rubber Processing Tech, Inc.
Osceola Mills, Pennsylvania
Tel: (814) 339-7924
- Mats and athletic & playground surfacing.

K & K Tires, Inc.
Linthicum, Maryland
Tel: (410) 636-2002
- Scrap tire recycler.

Liberty Tire Recycling
Braddock, Pennsylvania
Tel: (412) 351-5703
- Scrap tire recycler; TDA and rubber crumb manufacturer.

Little Earth Productions
Pittsburg, Pennsylvania
Tel: (800) 545-3784
Web: www.littlearth.com
- Make and distribute variety of handbags, wallets, key chains, and ties and belts from used tire inner tubes.

Magnus Environmental
Wilmington, Delaware
Tel: (302) 655-4443
Web: http://www.magnusenvironmental.com/
- Scrap tire recycler; TDA provider.

Recycling Technologies International, LLC
Hanover, Pennsylvania
Tel: (877) 633-9008 (717) 633-9008
Web: http://www.rtillc.com/
- Scrap tire recycler. TDA provider.

REC-creative, Inc.
Westminster, Maryland
Tel: (410) 876-0848
Web: www.recinc.com
- Distributor of recycled mats, tiles, athletic and playground surfacing for indoor and outdoor use.

Resource Revival
Portland, Oregon
Tel: (800) 866-8823
Web: http://resourcerevival.com
- Retail store and manufacture handmade belts, suspenders, picture frames, furniture, and key rings.

Rumber Materials, Inc.
Muenster, Texas
Tel: (940) 759-4181
Web: www.rumber.com
- Manufacture rubber/plastic lumber.

Signman Sign Co./Bike Games Ind.
Anderson, California
Tel: (530) 357-3156
Web: www.bikegames.com
- Manufacture custom imprinted mouse pad and beverage coasters using recycled rubber and plastic.

Splaff Flopps
San Diego, California
Tel: (619) 221-9199
Web: www.splaff.com
- Manufacture footwear using recycled tire tread soles, cushioning made from ground rubber, straps from recycled tube rubber.

Virginia Recycling Corp.
Providence Forge, Virginia
Tel: (804) 966-5159
- Scrap tire recycler; TDA provider.