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PENNDOT RESEARCH

PENNDOT

GUIDANCE DOCUMENTS FOR SCRAP TIRE UTILIZATION IN EMBANKMENTS

Transportation Materials Partnership

AGREEMENT NO. 359630, WORK ORDER 4

FINAL REPORT

September 2001

By H. Moo-Young, C. Ochola, D. Zeroka, K. Sellassie, G. Sabnis, C. Glass, and O. Thornton

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16. Abstract

At many local transportation projects in Pennsylvania, the cost of construction may be reduced by utilizing a waste or by product waste material to substitute conventional soils as fill material. The purpose of this document is to develop a product and material use approval process for state and local projects to utilize scrap tires as alternative to conventional aggregates and soils in embankments. As a result of this work, state and local projects will be able to take advantage of the Liquid Fuel Monies. The purpose of this document is to provide guidance on the utilization of scrap tires in embankments. This document contains the following sections:

a. Introduction to scrap tire utilization.
b. Physical-chemical properties of scrap tires.
c. Embankment design issues.
d. Design examples for scrap tires in embankments.
e. Laboratory testing of tire shreds.
f. A sample provisional specification.

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GUIDANCE DOCUMENT FOR SCRAP TIRE UTILIZATION IN EMBANKMENTS

Transportation Operation and Systems Research and Development Partnership
Agreement No. 359630
Work Order 4

FINAL REPORT

Prepared for

Commonwealth of Pennsylvania
Department of Transportation
Bureau of Environmental Quality

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Symbol	Name	SI Unit	English Unit
A	Cross Sectional Area	cm^2	in^2
b	Length	Meter	Feet
c	Cohesion	kN/m^2	lb/ft^2
c’	Effective Cohesion	kN/m^2	lb/ft^2
F_s	Factor of Safety	-	-
G_s	Specific Gravity	-	-
i	Hydraulic Gradient	-	-
k	Hydraulic Conductivity	cm/s	in/s
l	Length	Meter	Feet
m_α	Ratio of Factor of Safety of Slice		
N	Normal Force	kN	lb
Q	Flow Rate	cm^3/s	in^3/s
R	Radius of Failure Arc	Meter	Feet
S	Shear Force	kN	lb
t_{soil}	Thickness of Overlying Soil Layer	Meter	Feet
t_{scrap}	Compressed Thickness of Scrap Tires	Meter	Feet
u	Pore Pressure	kN/m^2	lb/ft^2
w	Water Content	%	%
W	Weight	kg	lb
□	Angle of Inclination of Slice	°	°
□	Angle of Slope	°	°
γ_d	Dry Unit Weight	kN/m^3	lb/ft^3
γ_t	Compacted Total Unit Weight	kN/m^3	lb/ft^3
γ_{tsoil}	Total Unit Weight of Overlying Soil	kN/m^3	lb/ft^3
γ_{tc}	Compressed Unit Weight of Tire	kN/m^3	lb/ft^3
ε_v	Percent Compression (Strain)	%	%
□	Angle of Friction	°	°
ϕ’	Effective Angle of Friction	°	°
σ’	Effective Stress	kN/m^2	lb/ft^2
□	Normal Stress	kN/m^2	lb/ft^2
σ_{vc}	Vertical Stress of Scrap Tire and Cover Soil	kN/m^2	lb/ft^2
σ_{vo}	Vertical Stress Caused by Scrap Tire	kN/m^2	lb/ft^2
□	Shear Strength	kN/m^2	lb/ft^2
τ’	Effective Shear Strength	kN/m^2	lb/ft^2

1. INTRODUCTION

1.1 PURPOSE

As society continues to generate waste and the cost of disposal continues to rise, government legislation has placed economic incentives and pressures on industries to recover and recycle these materials for use in secondary applications. Since highway construction requires large volumes of materials, highway agencies have been encouraged to participate in the recycling effort. Proper utilization of waste and by-product materials in transportation applications requires experience and knowledge regarding the use of these materials. Recovering these materials for potential use requires an awareness of the properties of the materials, how they can be used, and what limitations are associated with their use.

Management programs to alleviate the scrap tire disposal problem exist in almost every state. These programs incorporate laws, restrictions, and incentives for eliminating the stockpiles of waste tires. For example, Pennsylvania is one of 25 states that ban the disposal of whole tires in landfills. The state offers a price preference for state purchase of supplies that meet recycled content requirements. Pennsylvania also offers low interest loans for recycling research and development projects. The Pennsylvania Department of Transportation (PENNDOT) initiated/conducted two rubber-modified asphalt paving projects in 1998. Moreover, the Municipal Waste Planning, Recycling, and Waste Reduction Act (Act 101) examined the use of whole tires over landfill covers to mitigate the problem of tires floating in landfills. A $1/tire fee on new tire sales was established to support mass transit systems and to reduce the number of disposed tires (FHWA, 1998; Gupta, 1998; U.S. EPA, 1999).

Management programs, like those in Pennsylvania, exist all over the country. The state highway departments such as PENNDOT are among the largest consumers of virgin materials and may provide a potential marketplace for recycling tires. A mandate passed in the early 1990s titled, "The Intermodal Surface Transportation Efficiency Act" mandated the use of recycled rubber in any federally assisted asphalt pavement project. Unfortunately, the mandate was revoked in 1996 (U.S. EPA, 1999).

At many local transportation projects in Pennsylvania, utilizing industrial co-product materials to substitute for conventional soils as fill material may reduce the cost of construction (Van Tassel et al., 1999). Shredded or chipped tires have been used as a lightweight fill material for construction of embankments in several states. The purpose of this document is to provide PENNDOT with background information and guidance on the utilization of scrap tires in embankments. This document will provide the reader with an overview of scrap tires, physical and chemical properties of scrap tires, design criteria for embankments, embankment design example, laboratory testing results of scrap tires, and a sample specification.

1.2 OVERVIEW OF SCRAP TIRES

In the United States approximately 266 million scrap tires, or one tire per U.S. resident, are disposed of every year (Scrap Tire Management Council, 1998a; U.S. EPA, 1999). An estimated 78 percent of those tires are landfilled or illegally dumped. Currently, over 2 billion tires are stockpiled in landfills, deserts, forests, grasslands, and empty lots around the United States (Edil and Bosscher, 1994; Scrap Tire Management Council, 1997). To prevent further stockpiling of waste tires, 49 states have passed some type of law or regulation addressing scrap tire management. Twenty-five states ban scrap tires from landfills entirely (U.S. EPA, 1999).

While scrap tires only represent approximately 1.2 percent of all solid waste generated in the U.S., tires pose a significant disposal problem because their composition makes them non-biodegradable, bulky, and compaction resistant (Blumenthal and Zelibor, 1992; Cecich et al., 1996). The average automobile tire weighs 20 pounds (9.07 kg), with a typical casing composed primarily of carbon, hydrogen, sulfur, and ash. Eighty-five percent of disposed tires are automobile tires, 14 percent are the heavier truck tires ranging in weight from 35 to several hundred pounds (15.88 to several hundred kg). The additional 1-percent of disposed tires are specialty tires from aircrafts, and construction and mining equipment (Schnormeier, 1992; Lund, 1993; Scrap Tire Management Council, 1998b). The information regarding scrap tire generation is summarized in table 1.1 (U.S. EPA, 1999; Scrap Tire Management Council, 1997).

About 7 percent of the 266 million scrap tires generated annually are exported to foreign countries, 8 percent are recycled into new products, and roughly 40 percent are used as tire-derived fuel, either in whole or chipped form. Currently, the largest single use for scrap tires is as a fuel stock in power plants, cement plants, pulp and paper mill boilers, utility boilers, and other industrial boilers. In 1994, at least 100 million scrap tires were used as an alternative fuel either in whole or chipped form. In addition, at least 9 million scrap tires are processed into ground rubber annually for asphalt applications (Scrap Tire Management Council, 1997).

1.3 DEFINITIONS OF SCRAP TIRES

Scrap tires can be managed as whole, slit, shred, chip, ground rubber, or crumb rubber. Although this document will emphasize the use of tire shreds in embankments, this section of the document provides the reader with a general overview of the types of scrap tires. Tire cutting machines produce slit tires by first cutting it into halves and then separating the sidewall from the tread of the tire. Tire shreds are pieces of scrap tires that have a basic geometrical shape (i.e., rectangles and squares) and are generally between 50 and 305-mm in size. They are flat, irregularly-shaped tire chunks that may contain steel belts or beads. The production of tire shreds or tire chips involves primary and secondary shredding. Tire chips are pieces of scrap tires that have a basic geometrical shape (i.e., rectangles and squares) and are generally between 12 and 50-mm in size and have most of the wires removed (Humphrey, 2000; Read et al., 1991).

Ground rubber may be sized from particles as large as 19-mm to as fine as 0.15-mm (No. 100 sieve) depending on the type of size reduction equipment and the intended application. The production of ground rubber is achieved by using granulators, hammer mills, or fine grinding machines. Granulators typically produce particles that are regularly shaped and cubical with a comparatively low-surface area. A magnetic separator removes the steel belt fragments. Fiberglass belts or fibers are separated from the finer rubber particles, usually by an air separator. Ground rubber particles are subjected to a dual cycle of magnetic separation, then are screened and recovered into various size fractions (Blumenthal and Zelibor, 1992; FHWA, 1998).

Crumb rubber usually consists of particles ranging in size from 4.75-mm (No. 4 sieve) to less than 0.075-mm (No. 200 sieve). Most processes that incorporate crumb rubber as an asphalt modifier use particles ranging in size from 0.6 to 0.15-mm (No. 30 to No. 100 sieve). The cracker mill, granulator, and cryogenic techniques produce crumb rubber in particle sizes ranging from 0.15 to 0.6-mm, 0.5 to 5-mm, and 0.075 to 0.5-mm, respectively (FHWA, 1998; Heitzman, 1992).

1.4 USE OF SCRAP TIRES IN ENGINEERING APPLICATIONS

Virtually every tire component has commercial value. Tire Derived Fuel (TDF) constitutes approximately 67 percent of all tire reuse (Dodds, 1983; Dufton, 1995; Enerco Associate, 1986; B.C. Environment, 1991; Wallman et al., 1998; Cummings, 1998). Stockpiling and civil engineering applications compose 24 percent and 4 percent of scrap tire recycling, respectively. Other applications for scrap tire recycling include production of plastic products, joint and crack sealants, and roofing products. Table 1.2 summarizes the engineering applications for scrap tires.

Civil Engineering applications for scrap tires (Herein referred to as tire shreds) include lightweight fill, conventional fill, retaining wall and bridge abutment, insulation layer, and drainage applications. The use of tire shreds as lightweight fill in embankments and retaining walls has the following advantages (Humphrey, 2000):

a. Geotechnical: Light weight; free draining, low earth pressure, good thermal insulation, and durable.
b. Environmental: Reduces stockpiles of scrap tires, which are prone to fire and health hazards, and saves landfill space and land.
c. Economical: Low cost, conserves natural aggregate resources, and eliminates disposal cost.

Earth structures using tires as fill or tires mixed with soil have more flexibility than conventional structures and are able to withstand large differential settlements. Design parameters for embankments constructed using scrap tires are based on laboratory model studies, numerical analyses, and field performance of test fills that have been have been conducted by various researchers (Ahmed and Lovell, 1992; Edil and Bosscher, 1992; Humphrey et al., 1992; Humphrey and Manion, 1992; Bosscher et al., 1993; Foose, 1993; Humphrey et al., 1993; Humphrey and Sanford, 1993; Edil and Bosscher, 1994; Shakoor, 1995; Bernal, 1996; Cecich et al., 1996; Foose et al., 1996; Humphrey 1996a; Edil and Bosscher, 1997; Humphrey et al., 1997a, 1997b; Humphrey and Nickels, 1997; Oshaugnessy, 1997; Tatlisoz, 1997; Tatlisoz et al., 1997; Upton and Machan, 1997; Heimdahl and Drescher, 1998; Humphrey et al., 1998; Tweedie et al., 1998a; Tweedie et al., 1998b; Tweedie et al., 1998c; Chu, 1999; Lee et al., 1999; Humphrey et al., 2000). Moreover, it has been demonstrated that tire shreds can be used as lightweight fill for embankments (Humphrey, 1996a; Edil and Bosscher, 1997) and when properly designed tire shred fills do not experience a deleterious self-heating reaction (Rubber Manufacturing Association, 1997).

Due to geotechnical, environmental, and economic advantages, 13 states have utilized tire shreds or chips as a lightweight fill material for the construction of embankments or backfills. Some projects have used tire shreds or chips as embankment material, while other projects have blended tire chips with soil. In general these projects aimed to utilize tire shreds or chips to improve the geotechnical properties at the site. For example, at the Topsham–Brunswick bypass project in Maine, tire shreds replaced conventional fill behind a retaining wall to reduce the earth pressures and to mitigate settlement caused by a compressible foundation soil. In addition these projects took advantage of economic incentives in their respective states (e.g., in Washington state, using tire shreds in embankment construction saved King County $100,000 in landfill disposal fees). The states that have used tire shreds or chips in embankments include Colorado, Indiana, Maine, Minnesota, New York, North Carolina, Oregon, Texas, Vermont, Virginia, Washington, Wisconsin, and Wyoming (Read et al., 1991; Whitmill, 1991; Bosscher et al., 1993; Benda, 1995; Humphrey, 1996b; Stedge, 1996; Edil and Bosscher, 1997; Han, 1998; Hoppe, 1998; Dickson et al., 1999; New York State DOT, 1999; Colorado DOT, 2000; Indiana DOT, 2000; North Carolina DOT, 2000). Table 1.3 lists the scrap embankment projects and includes the basic features of each project such as the year, location, tire size, cap height, tire height, and type of fill. Only seven states (North Carolina, Oregon, Minnesota, Washington, Colorado, Indiana, and New York) have prepared some guidance for their use, as described in Appendix A.

1.5 ISSUES WITH SCRAP TIRE EMBANKMENTS

Since 1988, more than 70 tire shred fills with a thickness of less than one meter, and an additional 10 fills with a thickness of 4-m have been constructed (US. EPA, 1999). In 1995, three fills with a thickness over 8-m experienced a catastrophic internal heating reaction. Two additional fires necessitated the development of design guidelines that occurred in Washington state in the fall and winter of 1995-1996. Separate roadways utilizing tire fills spontaneously heated and started a fire. These fires created fear among the engineering community and resulted in a drop in the use of recycled rubber. In 1995, before the fires occurred, 12 to 15 million tires were reused, while in 1996, only 3 to 5 million were used. The aftermath of both fires involved extensive site remediation to remove and treat toxic materials that had contaminated the surrounding soil and groundwater (Humphrey, 1996b; Nightingale and Green, 1997). Oxidation of the rubber or exposed steel belts was listed as a probable cause for each fire.

The encountered problems were primarily associated with thick fills that had a large amount of crumb rubber particles exposed to significant amounts of water. To prevent oxidation reactions, fills including tires have been redesigned to contain layers no thicker than 3-m, and no organic soils allowed (Rubber Manufacturer Association, 1997) (Note that Appendix A has the Rubber Manufacturer Association's Guidelines to Minimize Internal Heating of Tire Shred Fills). The following conditions promote oxidation reactions:

a. Free access to air and water,
b. Retention of heat caused by high insulating value of tire shreds in a large fill thickness (Fills > 3 m).
c. Large amounts of exposed steel belts.
d. Smaller tire shred sizes and excessive amounts of granulated rubber particles.
e. Presence of inorganic and organic nutrients that enhance microbial activity (Zarpas, 1990; Schroeder, 1994;Office of State Fire Marshall, 1995; Rubber Manufacturers Association, 1997).

General design guidelines are now in place to minimize the risk of such reactions. For example, the largest shred should be less than 0.6-m in length. The shreds should be free of all contaminants such as oil and grease. The tires used for civil engineering applications should have never been exposed to fire. Heat liberates petroleum products that may later trigger another heating reaction. Design guidelines are less stringent for thinner fills where the risk of a tire fire is not as great. Fills are classified into two different categories. Class I Fills have a thickness of less than 1-m, while Class II Fills are 1 to 3-m thick (Rubber Manufacturer Association, 1997). Appendix A includes the design guidelines provided by the Rubber Manufacturers Association (1997).

Water quality is a concern with the use of industrial byproducts and recycled materials. Many different hydrocarbons and metals comprise tires. A five-year study on the effect of tire shreds placed above the water table was conducted on a secondary state highway in Maine. Results of this study determined that the effects of using recycled tires on groundwater were negligible (Humphrey et al., 1997b).

Table 1.1 Scrap Tire Generation.

Source	Quantity
Passenger Replacement	175,328,000
Light Truck Replacements	27,605,000
Medium, Wide Base, Heavy & Large Off-Road	11,139,000
Farming Sources	2,460,000
Tires from Scrapped Vehicles	49,476,000
Total Scrapped Tires	266,008,000
U.S. Population	265,100,000
Rate of Scrap Tire Generation	1.00 per person

(Adapted from U.S. EPA, 1999)

Table 1.2 Applications for Scrap Tires.

Scrap Tire	Application	References
Whole and Slit	Retaining Walls, Fuel, Artificial Reefs and Breakwaters, Erosion Control Systems, Sound Barriers	Dodds, 1983; Enerco Associate, 1986; B.C. Environment, 1991; Dufton, 1995; Sun, 1997; Cummings, 1998; FHWA, 1998; Wallman et al., 1998; Amari et al., 1999; Yang, 1999.
Shred	Retaining Walls, Embankments, Subgrade Fill, Backfill for Bridge Abutments, Subgrade Insulation, Landfill Construction, Septic Tank Drains, Highway Drainage Composites	Public Works, 1990; Eleazer, 1992; Upton and Machan, 1993; Cecich, 1994; Humphrey and Eaton, 1995; Song, 1995; Epps, 1996; FHWA, 1998; Chu, 1999; Lee et al., 1999.
Chip	Retaining Walls, Embankments, Subgrade Fill, Backfill for Bridge Abutments, Subgrade Insulation, Landfill Construction, Septic Tank Drains, Highway Drainage	Tatlisoz, 1996; Whetten et al., 1997; FHWA, 1998; Reid et al., 1998; Shakoor, 1998; Khatib and Bayomy, 1999; Saboudjian, 1999.
Ground Rubber	Asphalt, Aggregate, Rubber Products, Athletic and Recreational Applications, Frictional Materials Automotive Parts, Molded and Extruded Plastics, New Tires Septic Tanks, Hydro-Carbon Removal	Song, 1990; Park et al., 1993, Crouthamel, 1995; Lee, 1995; Park, 1995, Kim, 1996; Lee, 1996; Park et al., 1996; Dutta, 1998; FHWA, 1998, Winkler, 1998.
Crumb Rubber	Asphalt, Joint and Crack Sealant, Landscaping, Roofing Products, Rubber Products	Heitzman, 1992; Lee, 1995; 1996; Zanzotto, 1996; FHWA, 1998.

Table 1.3 Description of Scrap Tire Embankment Projects.

States	Year	Location	Tire Size (mm)	Cap Height (m)	Tire Height (m)	Type of Fill
Colorado	1995	Glenwood Canyon	50-300	0.6	21.3	Tire Shreds
Indiana	2001	LaPorte	50-300	0.9	1.8	Tire Shreds Mixed with Soil
Maine	1995	Portland Jet Port	50-300	2.44	3.05	Tire Shreds
	1995	North Yarmouth	50-300	0.76-1.37	0.6	Tire Shreds
	1995	Township 31MD	50-300	1.21-2.44	0.6	Tire Shreds
	1995	Orono	50-300	--	4.87	Tire Shreds
	1995	Topsham	50-300	1.82	4.26	Tire Shreds
	1995	Topsham	50-300	1.4	6.1	Tire Shreds
Minnesota	1990	Ramsey	50-300	1.2	1.8	Tire Shreds
	1990	Benton	50-300	1.2	0.91	Tire Shreds
	1990	Eden Prairie	50-300	1.67	2.74	Tire Shreds
	1990	Prior Lake	50-300	1.1	0.91	Tire Shreds
	1990	Milaca	50-300	0.61	0.91	Tire Shreds
	1990	Lake County	50-300	0.46	1.21	Tire Shreds
	1993	Pine City	50-300	0.46	0.91	Tire Shreds
New York	1999	Binghamton	50-300	1.5	3.0	Tire Shreds
N.Carolina	2001	TBA	12-50	---	1	Tire Chips
Oregon	1990	Roseburg	50-300	1.5	4.26	Tire Shreds
Texas	1995	El Paso	30-300	1	2	Tire Shreds and Soil Mix
Vermont	1991	Middlesex	--	0.6	3.0	Tire Chips
Virginia	1997	Route 199 overpass	max 25	1.5	7.5	Tire Shred Mixed with Soil
Washington	1995	Garfield	50-300		15	Tire Chips
	1995	Ilwaco	50-300	0.6	7.9	
Wisconsin	1991-1992	Madison	50-75	0.3	0.3	Soil and Tire Chips Layers

2. PHYSICAL-CHEMICAL PROPERTIES OF SCRAP TIRES

2.1 OVERVIEW

The purpose of this chapter is to provide an overview of the physical and chemical properties of scrap tires (tire shreds and chips). Tire shreds are flat, irregularly-shaped tire chunks with jagged edges that may or may not contain protruding, sharp pieces of metal, which are parts of steel belts or beads. A tire shredder is a machine with a series of oscillating or reciprocating cutting edges, moving back and forth in opposite directions to create a shearing motion, that effectively cuts or shreds tires as they are fed into the machine. The size of the tire shreds produced in the primary shredding process can vary from as large as 300 to 460-mm (12 to 18-in) long by 100 to 230-mm (4 to 9-in) as wide, down to as small as 100 to 150-mm (4 to 6-in) in length, depending on the manufacturer, model, and condition of the cutting edges. The shredding process results in exposure of steel belt fragments along the edges of the tire shreds (FHWA, 1998).

Tire chips are more finely and uniformly sized than tire shreds. Although the size of tire chips, like tire shreds, varies with the make and condition of the processing equipment, nearly all tire chip particles can be gravel sized. Production of tire chips requires two-stage processing of the tire shreds (i.e., primary and secondary shredding) to achieve adequate size reduction. Secondary shredding results in the production of chips that are more equal in dimension than the larger size shreds that are generated by the primary shredder, but exposed steel fragments will still occur along the edges of the chips.

2.2 CHEMICAL COMPOSITION

Scrap tires are non-reactive under normal environmental conditions. The principal chemical components of a tire are a blend of natural and synthetic rubber (Scrap Tire Management Council, 1998b). Scrap tires also contain both inorganic substances [pigments, fabrics, bead or belt materials, aluminum (Al), barium (Ba), chromium (Cr), iron (Fe), lead (Pb), manganese (Mn), sulfur (S), and zinc (Zn)] and organic substances [carbon black, polymers, oil, paraffin, volatile organic compounds such as 1,1-dichloroethane, and 4-methyl-2-pentanone and semi-volatile compounds such as 2-(4-morpholinyl)-benzothiazole]. Table 2.1 summarizes the chemical composition of scrap tires conducted for tire derived fuel (TDF) analysis.

2.3 ENGINEERING PROPERTIES

Physical properties of scrap tires include the particle shape and size, specific gravity, compacted unit weight, permeability, compressibility, and shear strength, and these properties vary depending on several factors (Foose et al., 1996; Humphrey and Nickels, 1997). Many of the procedures for testing soils and aggregates published by the American Society for Testing and Materials (ASTM) are also used to determine the properties of sieved tires. Tire shreds and chips are generally uniformly graded and their maximum size varies according to the manufacturing process. ASTM D422 determines particle size gradation. Figures 2.1a and b show typical gradation curves for tire shreds and chips, respectively. As previously noted, the size of tire shreds may range from as large as 460-mm to as small as 25-mm, with most particles within the 100-mm to 200-mm range. Tire chips are normally sized from 76-mm down to 13-mm. Figures 2.2a and 2.2b present digital photographs of tire shreds and chips, respectively.

The specific gravity (G_s) measures the ratio of the unit weight of solids of the scrap tires, γ_s, to the unit weight of water, γ_w, where $G_s = \gamma_s/\gamma_w$. The absorption capacity measures the amount of water that is absorbed onto the surface of the particles, and it is expressed as the percent of water based on the dry weight of the particles. ASTM C127 determines both the specific gravity and water adsorption. In general, the specific gravity of scrap tires is less than half the values obtained for coarse aggregate. In general, the specific gravity of scrap tires ranges from 1.02 to 1.27, whereas typical coarse-grained soils have specific gravities between 2.6 to 2.8. Table 2.2 provides a summary of specific gravity and water adsorption results for scrap tires that are categorized as glass belted, steel belted, and a mixture of glass and steel belted.

Compaction is the densification of soil by removing air through the application of mechanical energy (Das, 2000). Compaction tests on scrap tires are conducted by following ASTM D698 and D 1557 with modifications. ASTM D698 and D1557 are restricted to a six-inch (15.24-cm) compaction mold, which requires that no more than 30 percent is retained on the ¾-inch (1.9-cm) sieve. For scrap tires, a 10 to 12 inch (25.4 to 30.48-cm) mold is typically utilized. The compacted unit weight of scrap tires is about one quarter to one third that of conventional fills material-which makes tires ideal for a lightweight backfill material. Table 2.3 summarizes the results of laboratory compaction tests conducted by various researchers (Bressette, 1984; Edil and Bosscher, 1992; 1994; Humphrey et al., 1992; Manion and Humphrey, 1992; Ahmed, 1993; Ahmed and Lovell, 1993; Humphrey and Sandford, 1993). The average loose density of scrap tires varies according to the size of the shreds, but can be expected to be between 390 to 535-kg/m^3 (24-lb/ft^3 to 33-lb/ft^3). The average compacted density ranges from 650 to 840-kg/m^3 (40-lb/ft^3 to 52-lb/ft^3). Figure 2.3 shows a comparison of compacted dry density of scrap tires mixed with Ottawa sand and Crosby till (Ahmed, 1993). In general, as the dry weight of scrap tires increases, the density of the soil mixed with scrap tires decreases. Manion and Humphrey (1992) studied the effects of compaction energy on scrap tires and concluded that it has a small effect on the resulting dry unit weight. Moreover, they concluded that the water content does not significantly affect the compaction properties of the tire shreds.

Hydraulic conductivity relates the movement of a fluid through porous media resulting from a hydraulic gradient and is determined according to Darcy's Law:

$$Q = kiA \tag{2.1}$$

Where Q = Flow Rate (cm^3/s)
k = Hydraulic Conductivity, (cm/sec)
i = Hydraulic Gradient,
A = Cross-Sectional Area, (cm^2).

The hydraulic conductivity of scrap tires smaller than ¾ inch (1.9-cm) in size can be determined according to ASTM D2434. Larger diameter constant head permeameters ranging in size from 203 to 305 mm have been used to measure the hydraulic conductivity by numerous researchers (Bressette, 1984; Hall, 1990; Humphrey et al., 1992, 1993; Humphrey and Sandford, 1993; Edil and Bosscher, 1992, 1994; Ahmed, 1993; Ahmed and Lovell, 1993). The hydraulic conductivity of scrap tires is much greater than most granular soils, ranging from 1.5 to 15-cm/s. Table 2.4 summarizes the hydraulic conductivity of scrap tires and scrap tires mixed with Ottawa sand and Crosby Till. Figure 2.4 shows the hydraulic conductivity of scrap tires mixed with various percentages of subbase aggregate (Edil and Bosscher, 1992). As the percentage of scrap tires increases the hydraulic conductivity of the mixture increases. The high hydraulic conductivity is a benefit in construction with scrap tires since they allow for free drainage of water.

The compressibility of soils measures the amount of vertical displacement caused by the application of a load. Scrap tire compressibility is an important design consideration during construction and shortly after construction. The design of a scrap tire embankment must also take into account the settlement or deflection caused by a temporary load after construction such as the deflection of pavement caused by vehicle loads. The compressibility of scrap tires and scrap tires mixed with soils has been measured in large diameter containers by increasing the vertical stress (Manion and Humphrey, 1992; Humphrey and Manion, 1992; Humphrey et al, 1993; Humphrey and Sandford, 1993; Edil and Bosscher, 1992, 1994; Ahmed, 1993; Ahmed and Lovell, 1993; Drescher and Newcomb, 1994). When performing compressibility tests, it should be noted that the container must have sufficient diameter to accommodate the size of the scrap tire and the container should be lubricated to reduce the effects of sidewall friction. Figure 2.5a and b show typical stress and strain relationships for scrap tires at high and low stresses, respectively. In general, the compressibility decreases as the stress level increases.

Compressibility results are utilized to determine the in-place moist unit weight of tire shreds after they have compressed under the weight of the overlying tire shreds and soil. Humphrey (2000) outlines this approach as follows:

a. From laboratory compaction tests or typical values determined the initial uncompressed compacted dry unit weight of the scrap tires.
b. Estimate the in place water content of tire shreds (w) and use this value to determine the initial uncompressed, compacted total unit weight of tire shreds (γ_t)
$\gamma_t = \gamma_d (1 + w)$.

c. Determine the vertical stress in the center of tire shred layer (σ_{vc}).
d. To do this, first estimate the compressed unit weight of the scrap tires (γ_{tc})
$\sigma_{vc} = t_{soil} (\gamma_{tsoil}) + (t_{scrap}/2)(\gamma_{tc})$.
e. Determine the percent compression (ε_v) using σ_{vc} and the laboratory compressibility of the scrap tires.
f. Determine the compressed moist unit weight of the tire shreds:
$\gamma_{tc} = \gamma_t/(1+\varepsilon_v)$.

Humphrey (2000) also suggests a procedure to compute the overbuild of a scrap tire layer that is needed to result in a layer of a desired compressed thickness:

a. Determine the final in-place total unit weight of the scrap tires using the procedure outlined above.
b. Determine the vertical stress in the center of the scrap tire layer due to the weight of the scrap tires alone. $\sigma_{vo} = (t_{scrap}/2)[(\gamma_t + \gamma_{tc})/2]$.
c. Determine the vertical stress in the center of the scrap tires layer after the placement of the soil cover. $\sigma_{vc} = t_{soil} (\gamma_{tsoil}) + (t_{scrap}/2)(\gamma_{tc})$
d. Using the compressibility data for the scrap tires, determine the vertical strain corresponding to σ_{vo}, ε_{vo}, and the vertical strain corresponding to σ_{vc}, ε_{vf}.
e. The over build (OB) required to compensate for the compression of scrap tires is given by the following equation: $OB = t_{scrap} (\varepsilon_{vf} - \varepsilon_{vo})$.

The shear strength of scrap tires has been determined using direct shear apparatus in accordance with ASTM D3080 or triaxial shear apparatus. The large size of scrap tires has limited the utilization of the triaxial shear apparatus for tire shreds and chips less than 2.54-cm. Limited data are available on the shear strength of tire chips, while little or no such data are available on the shear strength of tire shreds. The wide variation in shred size makes it difficult to find a large enough apparatus to perform a meaningful shear test. Although the shear strength characteristics of tire chips vary according to the size and shape of the chips, internal friction angles were found to range from 19° to 26°, while cohesion values ranged from 4.3-kPa (90-lb/ft^2) to 11.5-kPa (240-lb/ft^2). In comparison, the typical values for the angle of friction for a sand range from 30° to 40°. However, unlike a typical sand, tire chips exhibit cohesion.

The shear strength of tire chips has been measured using triaxial tests by Bressette (1984), Ahmed (1993), and Benda (1995); and using direct shear by Humphrey et al. (1992, 1993), Humphrey and Sandford (1993), and Cosgrove (1995). Figure 2.6 shows a comparison of failure envelopes of scrap tires at low stresses. In general, the failure envelopes are non-linear. The shear strength of tire chips mixed with soil has also been investigated by numerous researchers (Hannon and Forsyth, 1973; Edil and Bosscher, 1992; Ahmed, 1993; Benson and Khire, 1995). It should be noted that under certain circumstances, the shear strength of soils may be increased by adding scrap tires (Benson and Khire, 1995).

Scrap tires can also be expected to exhibit high-insulating properties. If tire chips are used as a fill material in sub grade applications, reduced depth of frost penetration compared with that of granular soil can be expected. In general, the thermal conductivity of scrap tires is lower than conventional fill and soils. The thermal conductivity of scrap tires increases with increasing particle size, increasing water content, and increased compaction. Figure 2.7 illustrates the apparent thermal conductivity of scrap tires versus the density. Scrap tires have a heating value ranging from 28,000-kJ/kg (12,000-Btu/lb) to 35,000-kJ/kg (15,000-Btu/lb) and a thermal conductivity ranging from 0.2-0.35-W/m °C.

Table 2.1 Chemical Composition of Scrap Tires.

DESCRIPTION	%BY WT, AS RECEIVED	%BY WT, DRY BASIS
PROXIMATE ANALYSIS		
Moisture	0.62	----
Ash	4.78	4.81
Volatile Matter	66.64	67.06
Fixed Carbon	27.96	28.13
Total	100.00	100.00
ULTIMATE ANALYSIS		
Moisture	0.62	----
Ash	4.78	4.81
Carbon	83.87	84.39
Hydrogen	7.09	7.13
Nitrogen	0.24	0.24
Sulfur	1.23	1.24
Oxygen (by difference)	2.17	2.19
Total	100.00	100.00
ELEMENTAL MINERAL		
ANALYSIS (OXIDE FORM)		
Zinc	1.52	1.53
Calcium	0.378	0.380
Iron	0.321	0.323
Chlorine	0.149	0.150
Chromium	0.0097	0.0098
Fluoride	0.0010	0.0010
Cadmium	0.0006	0.0006
Lead	0.0065	0.0065
Heat Value (HV)	**BTU/lb**	**kJ/kg**
HV	16,250	37,798
HV Average	15,500	36,053
Tire Derived Fuel (TDF) Combustion		
Characteristics	**° F**	**° C**
Tires Ignite (Flash Point)	550 – 650	288 - 343
Carbon Begins to Burn	842	450
Carbon Completely Burnt	1202	650

(Adapted from Rubber Manufacturers Association, 1997).

Table 2.2 Summary of Specific Gravity and Water Adsorption Capacity.

Type of Tire	Apparent Specific Gravity	Water Adsorption Capacity	Reference
Glass Belted	1.14	3.8	Humphrey et al. (1992)
Glass Belted	1.02	4	Manion and Humphrey (1992)
Steel Belted	1.10	4	Manion and Humphrey (1992)
Mixture	1.18	9.5	Bressette (1984)
Mixture Palmer	1.24	2	Humphrey et al. (1992)
Mixture Sawyer	1.27	2	Humphrey et al. (1992)
Mixture	1.23	4.3	Humphrey et al. (1992)
Mixture	1.05	4	Manion and Humphrey (1992)
Mixture	0.88-1.13	--	Ahmed (1993)

Table 2.3 Summary of Laboratory Dry Unit Weight of Scrap Tires.

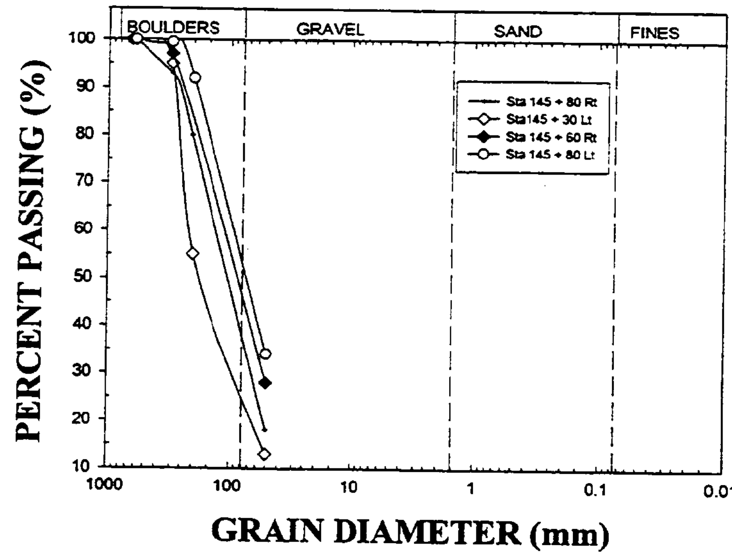
Method	Particle Size (inches)	Tire Shred Type	Dry Unit Weight (lb/ft^3)
Loose	3	Mixed	21.3
Loose	2	Mixed	30.1
Loose	1	Glass	30.9.25.5
Loose	2	Mixed	29.1
Loose	2	Mixed	30.5
Loose	1	Mixed	31.0
Vibration	1	Mixed	31.0
Vibration	0.5	Mixed	29.5
50% Standard	1	Mixed	38.3
50% Standard	0.5	Mixed	40.0
60% Standard	3	Mixed	38.7
60% Standard	2	Mixed	40.1
60% Standard	1	Glass	38.6
60% Standard	2	Mixed	39.0
Standard	2	Mixed	39.9
Standard	2	Mixed	39.6
Standard	1.5	Mixed	40.2
Standard	1	Mixed	40.7
Standard	0.5	Mixed	39.5
Standard	3	----	37.1
Standard	3	----	34.9
Modified	2	Mixed	41.2
Modified	2	Mixed	41.7
Modified	1	Mixed	42.7
------	2	Mixed	31

(Adapted from Bressette, 1984; Edil and Bosscher, 1992; Humphrey et al., 1992; Manion and Humphrey, 1992; Ahmed, 1993; Ahmed and Lovell, 1993; Humphrey et al., 1993; Humphrey and Sandford, 1993; Edil and Bosscher, 1994)

Table 2.4 Summary of Hydraulic Conductivity of Scrap Tires and Scrap Tires Blended with Soils.

Tire Size	Soil Type	% Tire	Dry Unit Weight (lb/ft^3)	Hydraulic Conductivity (cm/s)
2-2.5	---	100	29.0-38.1	2.9-59.3
0.75-1.5	---	100	---	0.8-2.6
1.5-3	---	100	38.8-52.0	1.5-15.4
1.5	--	100	65.3	0.58
1.5-3	---	100	41.7-53.6	1.5-16.3
—	Ottawa Sand	0	118	1.6×10^{-4}
1	Ottawa Sand	15.5	105	1.8×10^{-3}
1	Ottawa Sand	30.1	95.5	3.5×10^{-3}
1	Ottawa Sand	37.7	88.0	8.7×10^{-3}
—	Crosby Till	0	119	8.9×10^{-7}
1	Crosby Till	14.8	106	1.8×10^{-5}
1	Crosby Till	40	74.9	8.8×10^{-3}
0.5	Crosby Till	40	74.3	9.7×10^{-3}

(Adapted from Bressette, 1984; Hall, 1990; Humphrey et al., 1992; Ahmed, 1993; Humphrey et al., 1993; Lawrence et al., 1998).



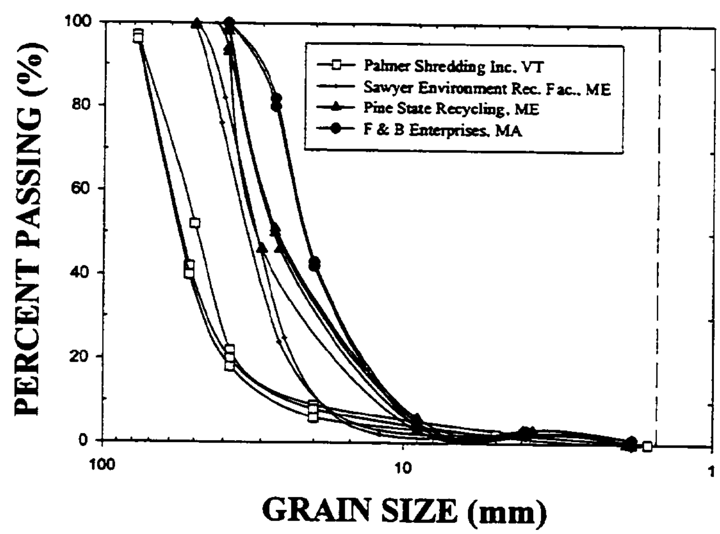
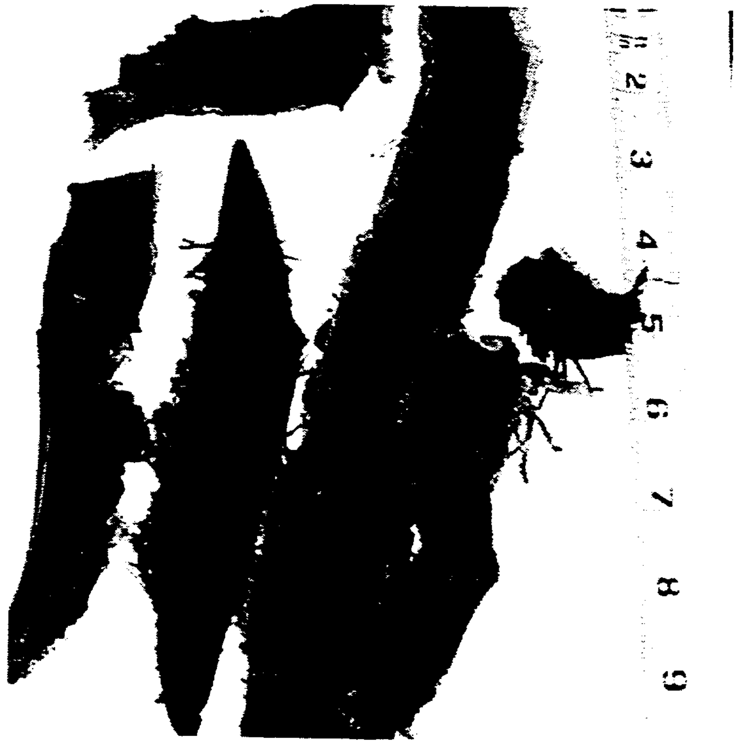


Figure 2.1a Gradation Curve for Tire Shreds (Adapted from Humphrey, 2000).
Figure 2.1b Gradation Curve for Tire Chips (Adapted from Humphrey, 2000).



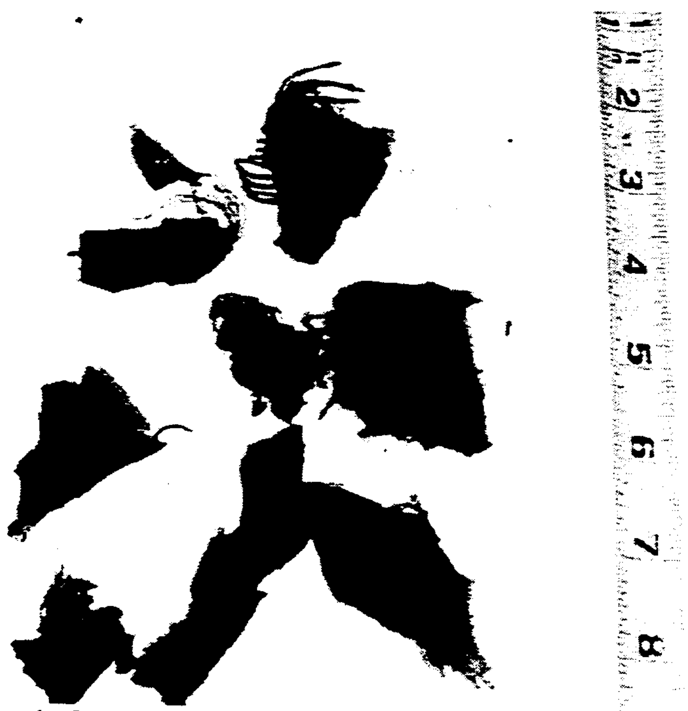


Figure 2.2a Tire Shreds Greater than 2-in.
Figure 2.2b Tire Chips Less than 2-in.

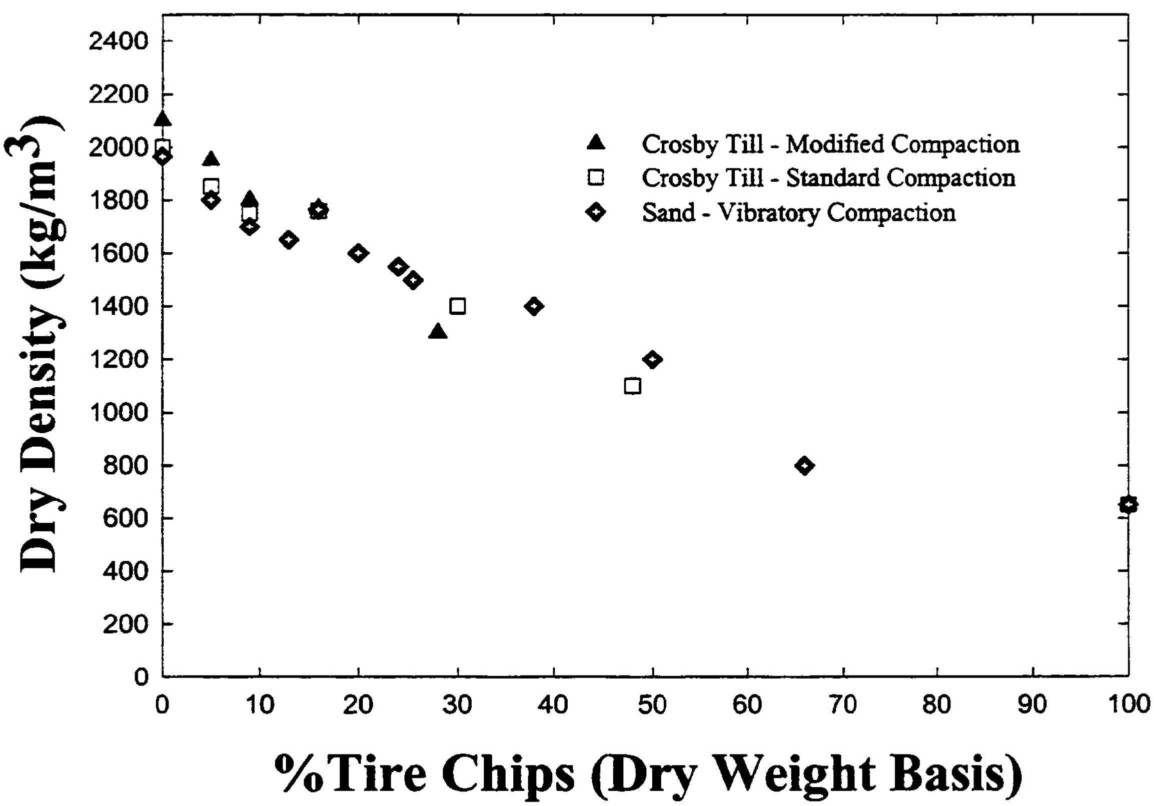


Figure 2.3 Comparison of Compaction Dry Density of Mixtures of Scrap Tires with Ottawa Sand and Crosby Till (Adapted from Ahmed, 1993).

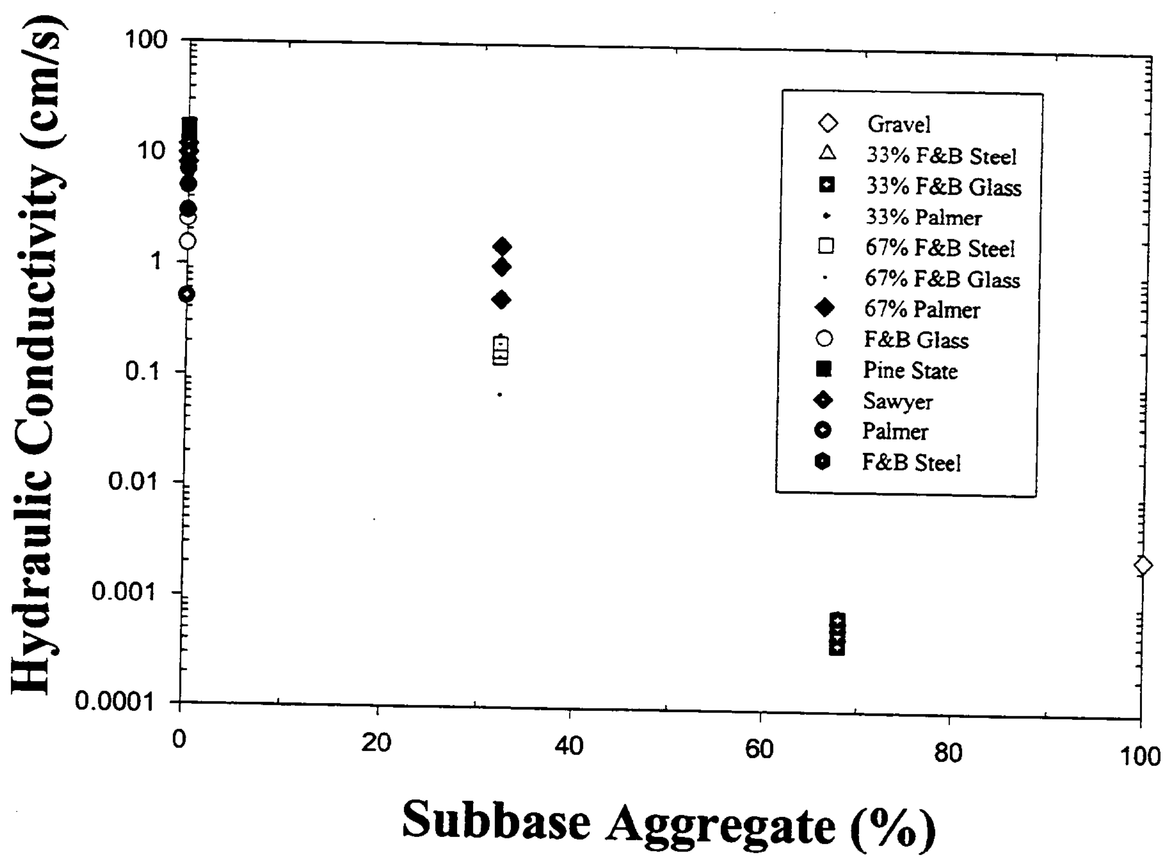
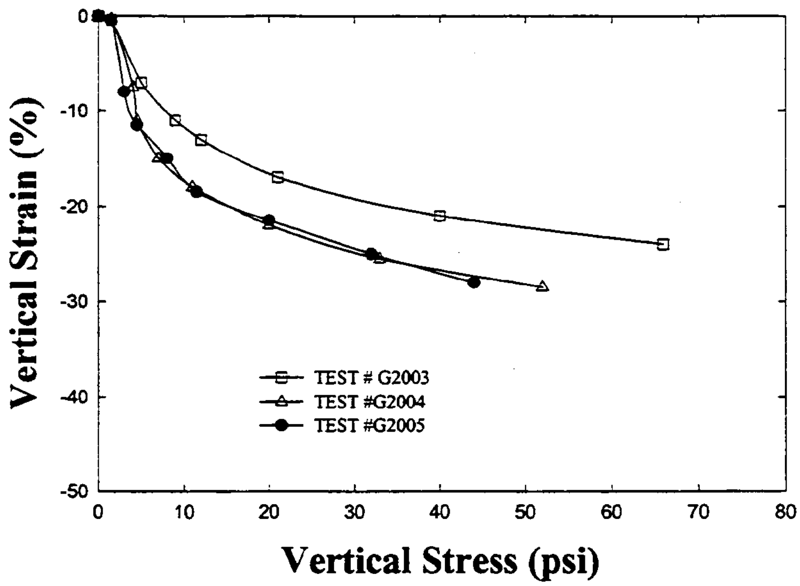


Figure 2.4 Hydraulic Conductivity of Tires and Sand Mixtures (Adapted from Edil and Bosscher, 1992).



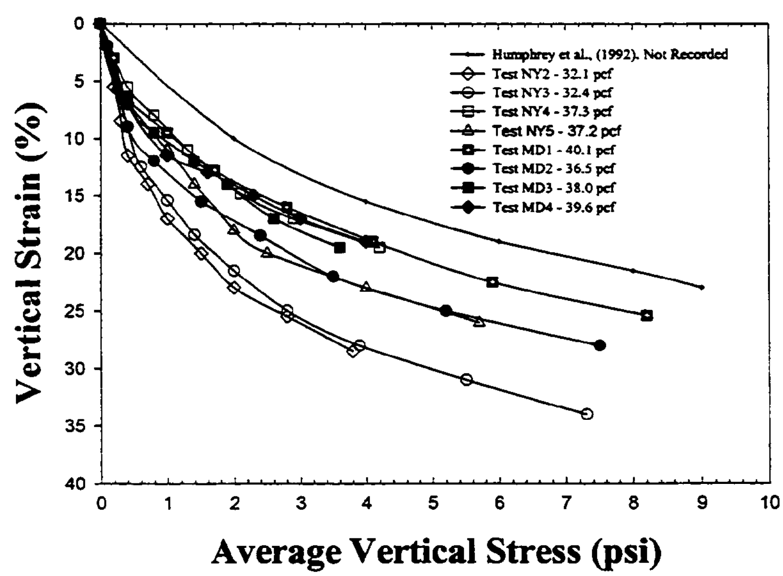


Figure 2.5a Compressibility of Scrap Tire at High Vertical Effective Stress (Adapted from Humphrey, 2000).

Figure 2.5b Compressibility of Scrap Tires at Low Effective Stress (Adapted from Humphrey, 2000).

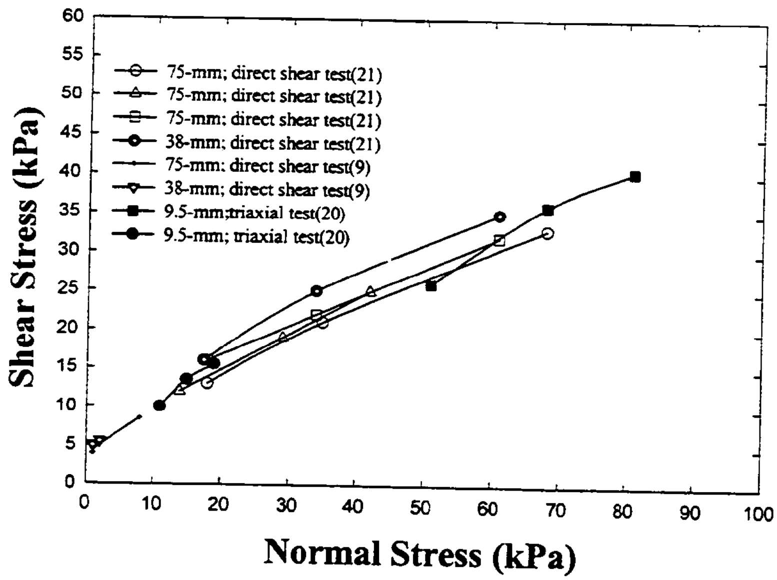


Figure 2. 6 Comparison of Failure Envelopes of Tire Shreds at Low Effective Stresses (Adapted from Humphrey, 2000).

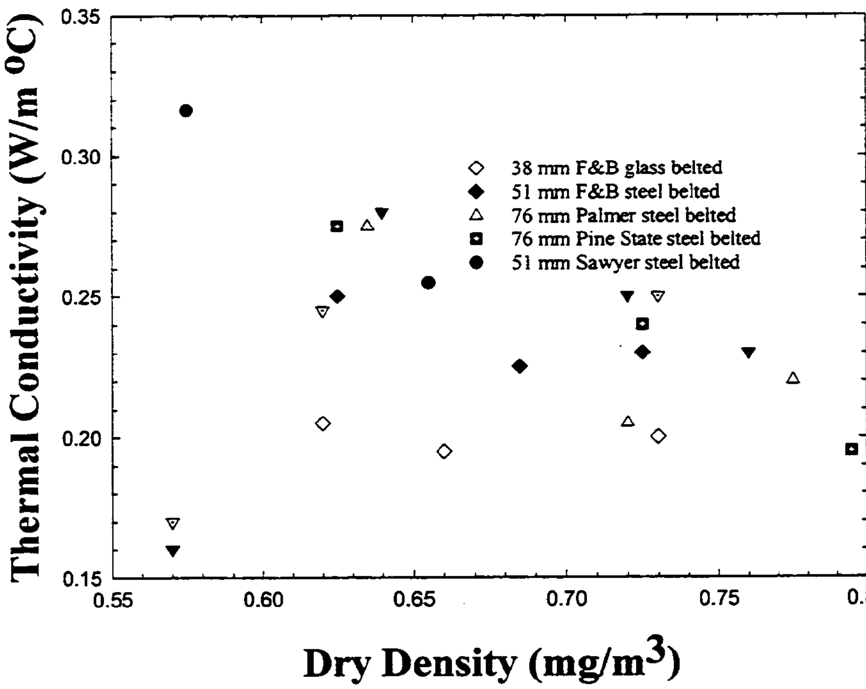


Figure 2.7 Thermal Conductivities of Scrap Tires (Adapted from Humphrey, 2000).

3. EMBANKMENT DESIGN ISSUES

Those familiar with the background and theory of the Ordinary Method of Slices and Bishop's Modified Method of Slices used for slope stability analysis may proceed to chapter 4. This review is provided for individuals not already familiar with these approaches.

3.1 DEFINITIONS

Earth embankments are used chiefly for railway and highway fills, levees, and earth dams. The earliest highway embankments were constructed by loosely dumping fill. The term slope refers to any earth mass, natural or man-made, whose surface forms an angle with the horizontal. Man made slopes may include fills such as embankments and earth dams.

Earth masses with a constant inclination may be categorized by the extent of the slope. A slope that extends for a relatively long distance and has a consistent subsoil profile may be analyzed as an infinite slope. Natural slopes such as hills and mountains may be defined as infinite slopes. Finite slope is the earth masses of constant inclinations of limited extent (horizontal and vertical) and has uniform conditions at any given depth below the surface. Earth embankments may be categorized as finite slopes. Figure 3.1 shows a typical cross section of a highway embankment, where β is the slope angle and H is the height of the slope.

Whenever a mass of soil has an inclined surface, there is always a potential for part of the soil mass to slide from a higher location to a lower one. A slope is considered stable if it meets a prescribed need for a fixed period of time with a suitable or acceptable factor of safety. Sliding or slope instability occurs if the shear stresses developed in the soil exceed the corresponding shear strength of the soil. The shear stress of the soil is defined as the soil's ability to resist sliding along an internal failure surface within the soil mass. Figure 3.2 illustrates an example of the shear stress that occurs along a slope. A material with a weight of W rests on a slope at the angle β. The shear stress is proportional to the angle of the slope. Figure 3.2 also illustrates that steeper slopes experience greater shear stress.

The shear strength of a soil may be expressed by the Coulomb's equation:

$$\tau = c + \sigma \tan \phi \tag{3.1}$$

Where τ = shear strength (N/m^2)
c = cohesion (N/m^2)
σ = normal stress (N/m^2)
ϕ = coefficient of friction angle (°).

Cohesion (c) refers to the strength associated with mutual attraction between grain particles and is predominant in clayey soils. The angle of friction (ϕ) refers to strength gained from internal frictional resistance (this includes sliding and rolling friction and the resistance offered by interlocking action among soil particles) and is predominant in cohesionless soils (Lui and Evert, 2001). Figure 3.3 shows the typical modes of failure for slopes.

3.2 SLOPE STABILITY

The aim of embankment slope design is to determine a fill height and slope angle that is both stable and economical. Geological conditions and insitu material properties influence slope design. Immediate and sudden failure must be prevented and the slope must be protected over the long term, unless the slope is cut for temporary reasons only. Embankment stability at the end of construction may be a critical design consideration.

The short and long term slope stability must be analyzed prior to construction. Short term usually refers to the end of construction (i.e., excavation) and is generally due to excessively steep slopes and may occur within a relatively short time after excavation. Long term usually refers to the dissipation of the negative excess pore pressure and usually triggers failure of slopes that are not properly designed. The stability of slopes is generally a function of the shear strength parameters (total or effective), slope angle and height, unit weight of soil, and pore water pressure. Laboratory tests are conducted to evaluate the in-situ engineering properties of the fill. In general, embankment slopes are designed using shear strength parameters obtained from tests on samples of the proposed material compacted to the anticipated field conditions. Embankments and fills do not usually involve the same analytical difficulties and uncertainties as natural slopes and cuts because borrow materials are pre-selected and processed. Natural slopes and cuts are typically layered systems with two or more soil layers composing the slope.

Slope stability, can be mathematically defined in a number of different ways such as by rotational force equilibrium, rotational moment equilibrium, or sliding wedge force equilibrium. The analysis of stability necessitates the hypothesis of a failure surface, the determination of driving and resisting forces, and the definition of a factor of safety employing these force systems. The driving forces are from the weight of the soil mass, and applied surface loads and the resisting forces result from the strength of the soils. Since a variety of possible failure planes can be considered, the critical failure surface is the surface associated with the lowest calculated factor of safety for the embankment configuration, center of rotation and soil materials. In general, slope failures in embankments occur in one of the following modes as shown in Figure 3.1:

a. *Slope failure.* When the failure occurs in such a way that the surface of sliding intersects the slope at or above the toe of the slope.

b. *Base Failure.* When the failure occurs in such a way that the surface of sliding passes at some distance below the toe of the slope.

c. *Toe Failure.* The failure circle passes through the toe of the slope.

d. *Failure through the fill and foundation.* The failure surface passes through the underlying foundational materials.

Procedures for stability analysis are divided into two general categories: mass procedures and method of slices. In mass procedures, the soil mass above the sliding surface is taken as a unit. This procedure is useful when the slope is assumed to be homogenous as in a clay. The method of slices divides the soil above the surface of sliding into a number of vertical parallel slices and is useful in analyzing layered soil systems. This document will discuss the method of slices procedure in depth since it is utilized by PENNDOT to analyze for slope stability.

The method of slices assumes that the failure occurs along a curved surface. In applying the method of slices, a cross section of the slope is drawn to scale. Figure 3.3 shows the trial curved surface where sliding is assumed to have taken place. A circle is typically assumed for trial surface. The soil contained in the trial surface and the slope is divided into a number of vertical slices. Assuming that the problem is two dimensional, the soil weight of each slice is calculated by multiplying the slice volume by the soil unit weight.

Figure 3.4 illustrates a single slice from the failure surface. The weight of the soil, W, represents a downward vertical force, and can be resolved into a normal force, W_n, and a force parallel, W_p, with the base of the slice. The parallel force causes sliding of the surface. Resistance of the soil to sliding is attributed to the cohesion and angle of friction of the soil. The cohesion force is equal to the soil's cohesion multiplied by the length of the slice. The friction force is equal to the normal force, W_n, multiplied by the tangent of the angle of friction ($W_n = W \cos \alpha \tan \phi$, where α is the angle of inclination of slice).

The total force that tends to cause sliding is equal to the summation of the parallel forces of each slice which is equal to the weight of the soil times the sine of the angle of inclination of the respective slices. The total resistance of the soil to sliding is equal to the summation of the cohesive force plus the normal force. The factor of safety (F_s) against sliding is equal to the ratio of the resisting force to the sliding force:

$$F_s = \frac{\sum_{i=1}^{n} cl + W \cos \alpha_{avg} \tan \phi}{W \sin \alpha} \tag{3.2}$$

This method gives the factor of safety for an assumed failure surface. It should be noted that the circular failure surface selected might not be the weakest. Therefore, it is essential to analyze several failure surfaces (Das, 2000; Lui and Evett, 2001).

Bishop (1955) presented a more refined method of analysis and is the most widely used for slope stability analysis. His method uses static equilibrium considerations rather than finding a factor of safety against sliding by computing the ratio of the total force resisting sliding to the total force tending to cause sliding. Consider a representative slice as shown in Figure 3.5. Figure 3.5 shows all the forces acting on the slice and the forces on the base where W is the weight, T is the shear force, H is the normal force on the sides, and S and N are the shear and normal force on the base. Bishop showed that the equilibrium of the sliding mass requires that:

$$R\sum W\sin\alpha = R\sum S \tag{3.3}$$

Where R is the radius of the assumed failure surface. At the base of the slice, the shear force is equal to the following:

$$S = \frac{\tau l}{F_s} = \frac{\tau b}{F_s \cos\alpha} \tag{3.4}$$

Where τ is the shear strength, l and b are the dimensions of the slice, and α is the angle of inclination of the slice taken through the midpoint of the base of each slice. If equation 3.4 is substituted into equation 3.3, the factor of safety can be computed as follows:

$$F_s = \frac{\sum(\tau b/\cos\alpha)}{\sum W\sin\alpha} \tag{3.5}$$

The shear strength is determined by equation 3.1. The effective normal stress is evaluated by analyzing the vertical equilibrium of the slice shown in figure 3.6 where:

$$W = S\sin\alpha + N\cos\alpha \tag{3.6}$$

Since the effective stress is equal to (N cos α)/b, equation 3.6 can be rearrange as follows:

$$\sigma' = \frac{W}{b} - \frac{S}{b}\sin\alpha \tag{3.7}$$

Substituting equation 3.7 into equation 3.1 yields the following:

$$\tau = c + (\frac{W}{b} - \frac{S}{F_s}\sin\alpha)\tan\phi \tag{3.8}$$

By substituting the value of τ into equation 3.8 and solving for τ, the following expression is obtained:

$$\tau = \frac{c + (W/b)\tan\phi}{1 + (\tan\alpha\tan\phi)/F_s} \tag{3.9}$$

This equation considered with equation 3.1 produces an interative series of equations. To simplify computations, let

$$m_\alpha = \left[1 + \frac{\tan\alpha \tan\phi}{F_s}\right]\cos\alpha \tag{3.10}$$

Substituting equation 3.10 into equation 3.9 and solving for the factor of safety yields the following:

$$F_s = \frac{\sum_{i=1}^{n} \frac{cb + W\tan\phi}{m_\alpha}}{\sum_{i=1}^{n} W\sin\alpha} \tag{3.11}$$

The factor of safety in equation 3.11 must be solved iteratively since the value of m requires a value for the factor of safety. The correct factor of safety is obtained when the assumed factor of safety equals the computed value. The ordinary method of slices provides conservative estimates of slope stability (Das, 2000; Lui and Evett, 2001).

3.3 LAYERED DESIGN APPROACH

In the design of a layered slope, the shear strength parameters are of paramount importance in slope stability calculations. At the slip surface, the soils are at or near the critical or residual state. In conducting stability calculations, the shear strength parameters at the critical state should be utilized. Equation 3.12 shows the simplified Bishop method applied to a layered soil system.

$$F_s = \frac{\sum_{i=1}^{n} \frac{c_{cr}b + W\tan\phi_{cr}}{m_\alpha}}{\sum_{i=1}^{n} W\sin\alpha} \tag{3.12}$$

To illustrate this procedure using figure 3.3, assume that soil 1 has a cohesion of 30-kPa and an angle of friction of 33°and soil 2 has a cohesion of 58-kPa and an angle of friction of 25°. On the proposed failure surfaces, critical shear strength parameters for slices 1 through 4 are those of soil 2. Slices 5 and 6 exhibit critical shear strength parameters of soil 1. It should be noted that in over consolidated clays, progressive failure usually occurs, and the residual shear strength parameters frequently govern.

3.4 PENNDOT EMBANKMENT DESIGN ISSUES

PENNDOT provides guidelines for embankment construction, which include the following:

- Section 206 (Embankments) of Publication 408
- PASTABLM User's Guide and computer program
- Standards for Roadway Construction, Publication 72M

Section 206 of Publication 408 provides the material specifications, construction requirements, and methods of payment for an embankment. PASTABLM is a program written in FORTRAN used to calculate the factor of safety against slope stability using a two-dimensional limit equilibrium model. The calculation of the factor of safety against slope instability is performed using the simplified Bishop method which is applicable to circular failure surfaces, simplified Janbu method which is applicable to failure surfaces of a general shape, or Spencer method of slices which is applicable to failure surfaces that have a circular or general shape. The program is capable of handling heterogeneous soil profiles, anisotropic soil parameters, excess pore water pressure, earthquake loads, surcharge and tieback loading, and reinforced slopes. PASTABLM iteratively searches for the failure surfaces using randomly selected radii and centers of rotational failures defined by the user. Additional information on PASTABLM is provided in the PASTABLM User's Guide. In general, slope stability analysis is conducted on slopes that are steeper than 2:1.

The Standards for Roadway Construction, Publication 72 M, provides drawings and notes for the classification of earthwork, classification of earthwork for structures, backfill at structures, subsurface drainage, and slope protection. From these figures, it is noted that the slope of a typical cross section of the embankment material does not exceed 1.5:1.

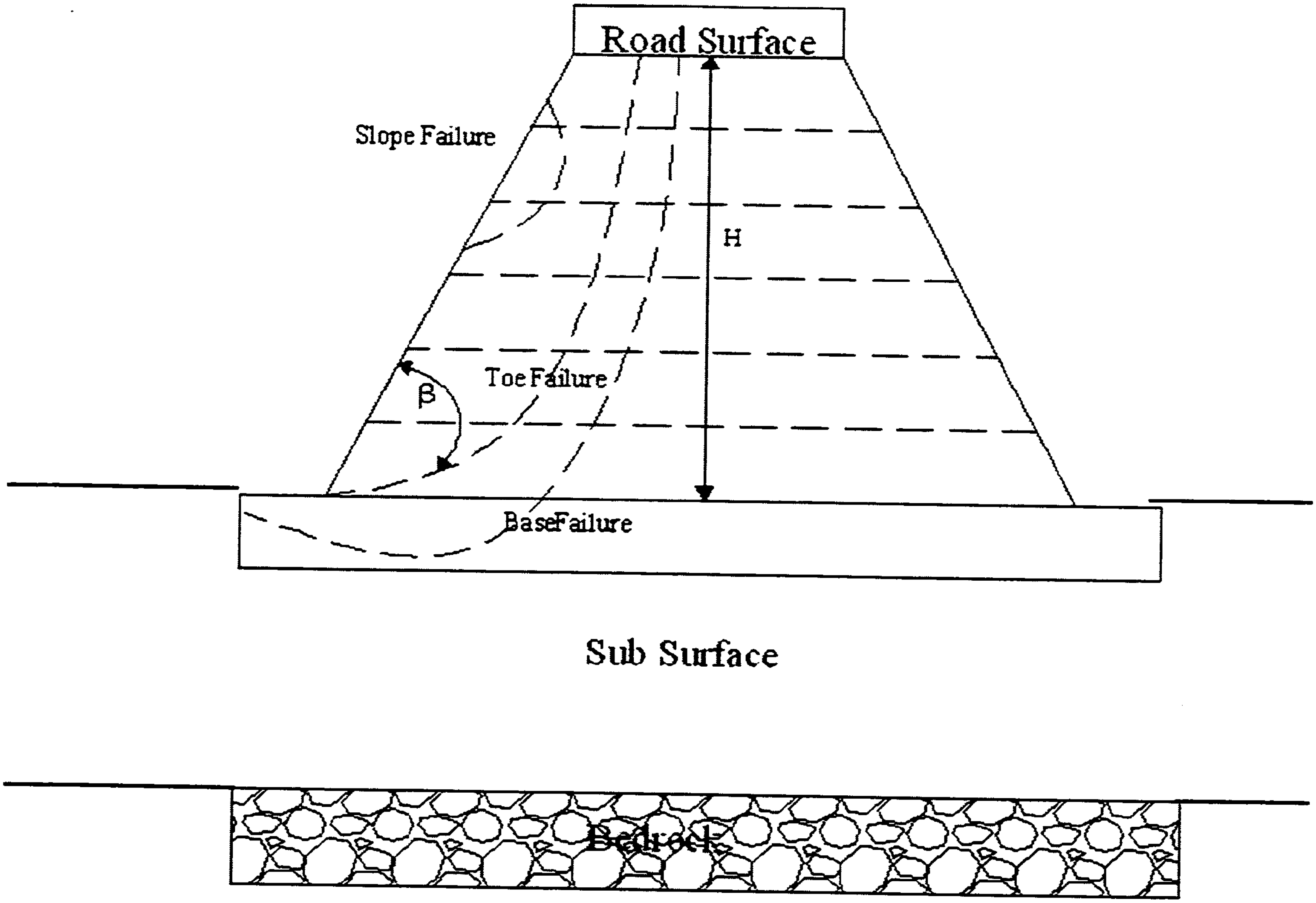
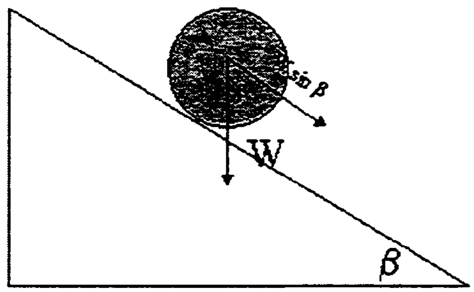


Figure 3.1 Sketch of a Typical Highway Embankment.



- Shear Stress is the most important class of stresses
- Results from weight of material, W and angle of the slope β
- The steeper the slope the greater shear stress

Figure 3.2 Shear Stress Example.

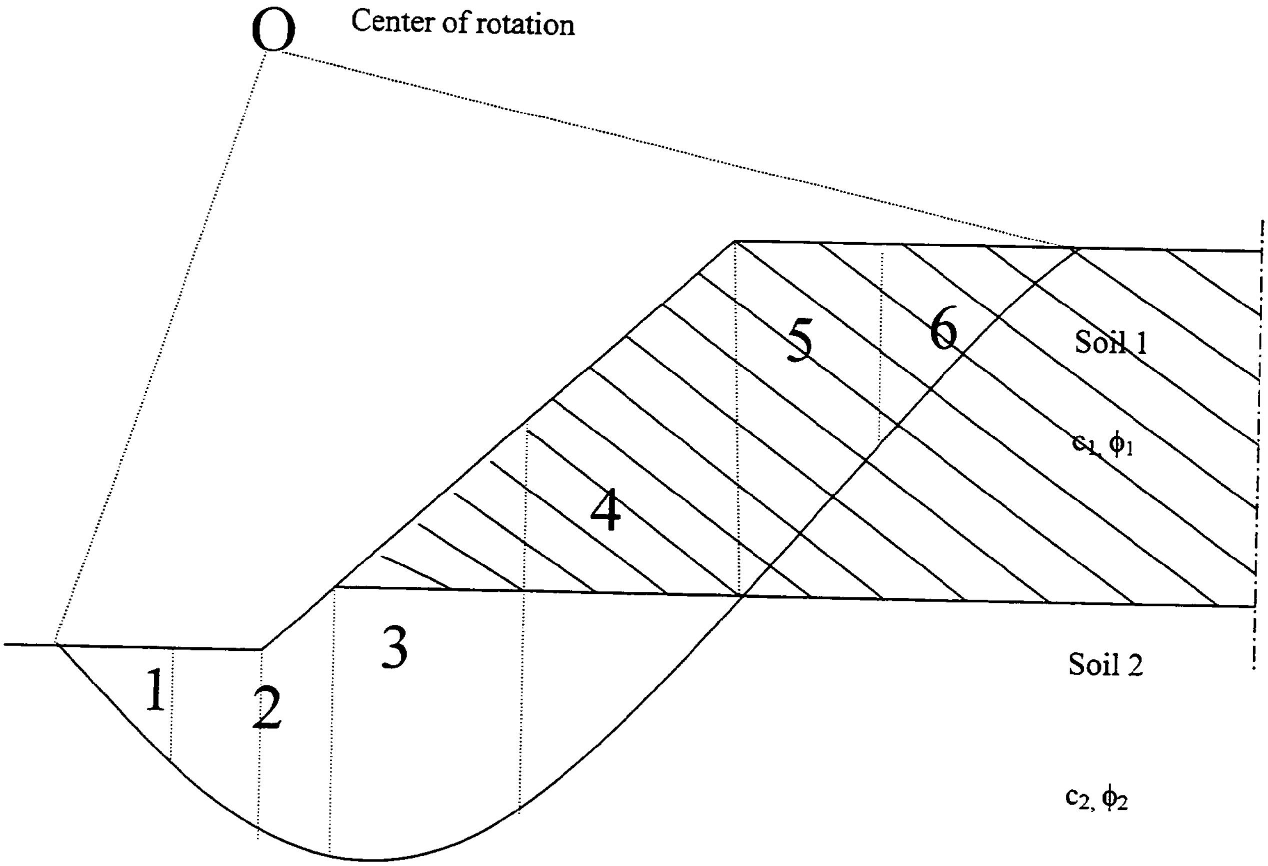


Figure 3.3 Trial Failure Surface for Method of Slices.

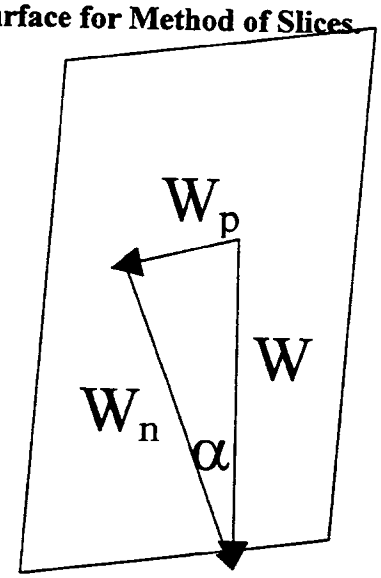
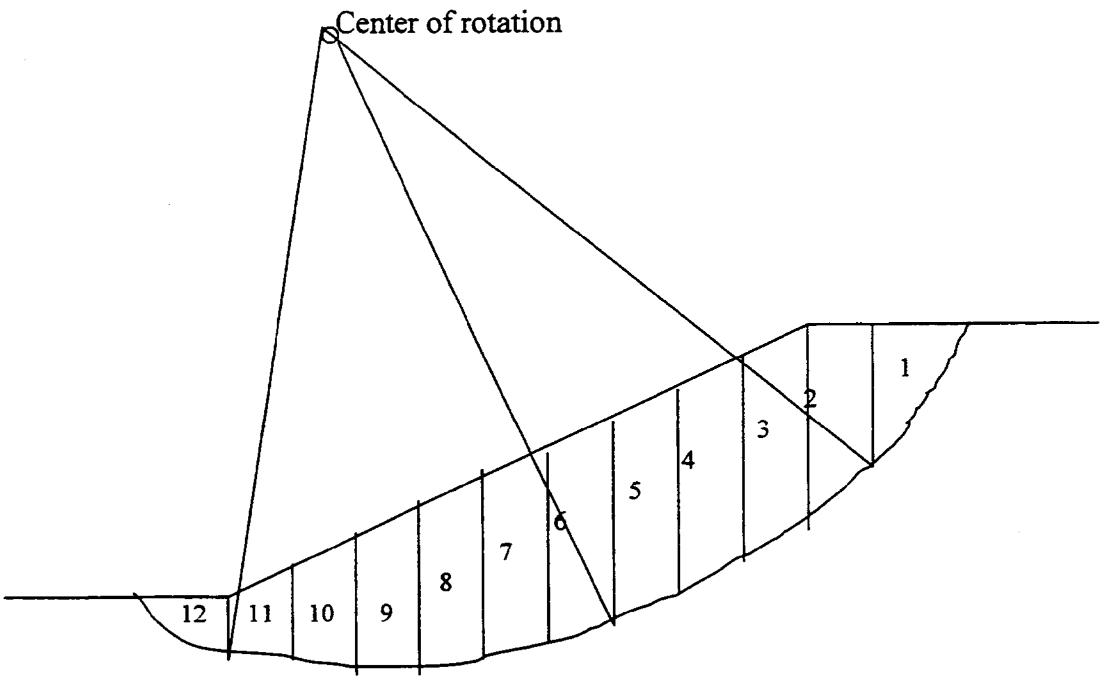


Figure 3.4 Force on a Single Slice

a)



(b)

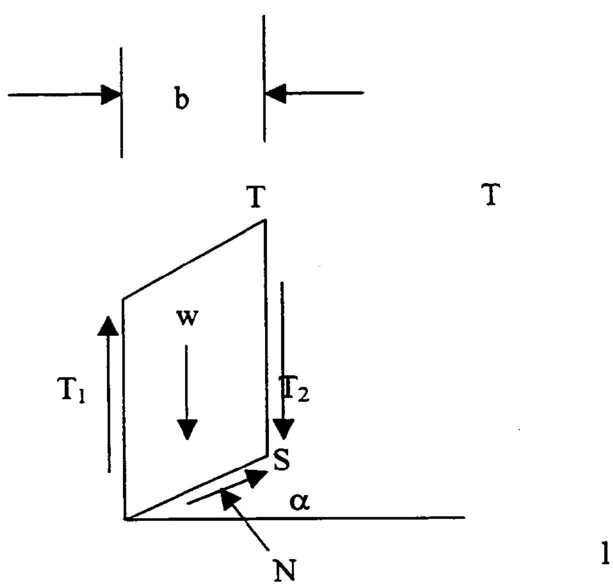


Figure 3.5 (a)Trial Failure Surfaces, and (b) Force on Single Slice for the Bishop Simplified Method of Slices.

4. DESIGN EXAMPLES

In this chapter, three example problems are illustrated to compare an embankment built with sand to scrap tires and a layered system composed of sand and tire shreds. The foundation soil in these examples is a soft clay with a low cohesion. In these problems, three slopes are compared with similar heights (H), radii (R) and failure surfaces. (Given H = 25 ft, R = 23.2 ft, and a slope of 1:1). The soil properties are as follows:

- Sand $\gamma = 120\text{-lb/ft}^3$, $\phi = 30°$, $c = 0\text{-lb/ft}^2$
- Tire Shreds $\gamma = 35\text{-lb/ft}^3$, $\phi = 25°$, $c = 125\text{-lb/ft}^2$
- Clay $\gamma = 127\text{-lb/ft}^3$, $\phi = 30°$, $c = 200\text{-lb/ft}^2$

4.1 EXAMPLE 1

Determine the factor of safety of the slope shown in figure 4.1 using the simplified Bishop method.

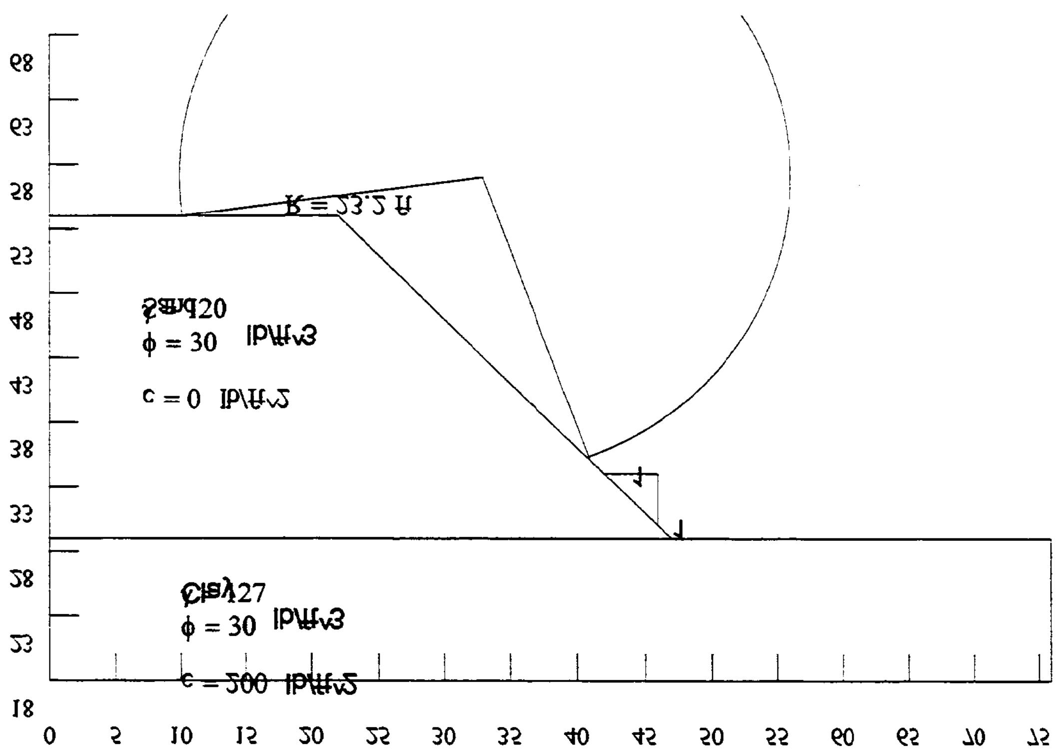


Figure 4.1 Example 1. Sand Embankment on Clay.

Solution:
Step 1: Draw the figure to scale.
Step 2: Divide the sliding mass into slices as shown in figure 4.2.
Step 3: Set up a spreadsheet as shown in table 4.1.
Step 4: Extract the required values from figure 4.2 and perform the calculations.

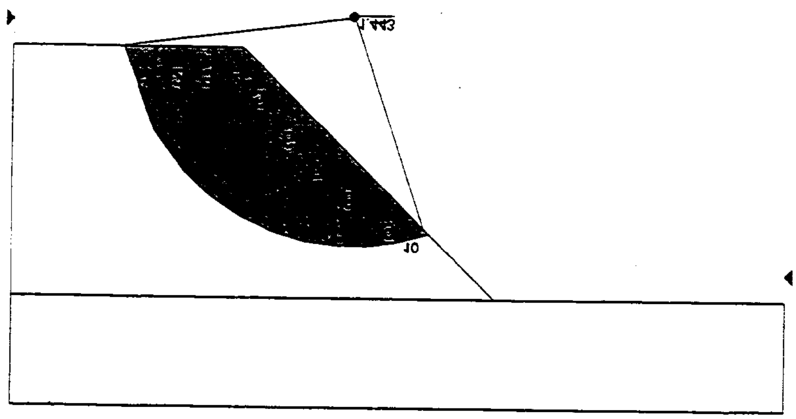


Figure 4.2 Graphical Solution to example 1.

Table 4.1 Solution to Example 1.

Slice Number	Slice Width B (feet)	Base Length l (feet)	Slice Angle α (°)	m_α	Weight W (lb)	$W \sin\alpha$ (lb)	$\frac{cb}{m_\alpha}$ (lb)	$\frac{W \tan\phi}{m_\alpha}$ (lb)
1	2.9	8.9	71.1	0.70	1919.3	1815.9	0	1577.8
2	2.9	4.9	53.1	0.92	3713.6	2989.8	0	2342.6
3	2.9	3.9	42.5	1.01	4825.3	3260.7	0	2765.2
4	2.9	3.5	33.2	1.06	5606	3069.8	0	3065.5
5	3.1	3.4	24.5	1.08	6004.2	2496.8	0	3222.2
6	3.1	3.2	16.3	1.07	5284.7	1479.6	0	2846.1
7	3.1	3.1	8.3	1.05	4389.1	633.06	0	2419.7
8	3.1	3.1	0.48	1.00	3332.8	28.4	0	1917.7
9	3.1	3.1	-7.3	0.94	2120.9	-269.7	0	1301.3
10	3.1	3.2	-15.2	0.86	749.4	-197.0	0	503.4
				SUM	37945.3	15307.6	0	21961.5

Using equation 3.11, the factor of safety is determined as follows:

$$F_s = \frac{\sum \frac{cb + W\tan\phi}{m_\alpha}}{\sum W\sin\alpha} = \frac{0 + 21961.5}{15307.6} = 1.4$$

4.2 EXAMPLE 2

Determine the factor of safety of the slope composed of scrap tires shown in figure 4.3 using the simplified Bishop method.

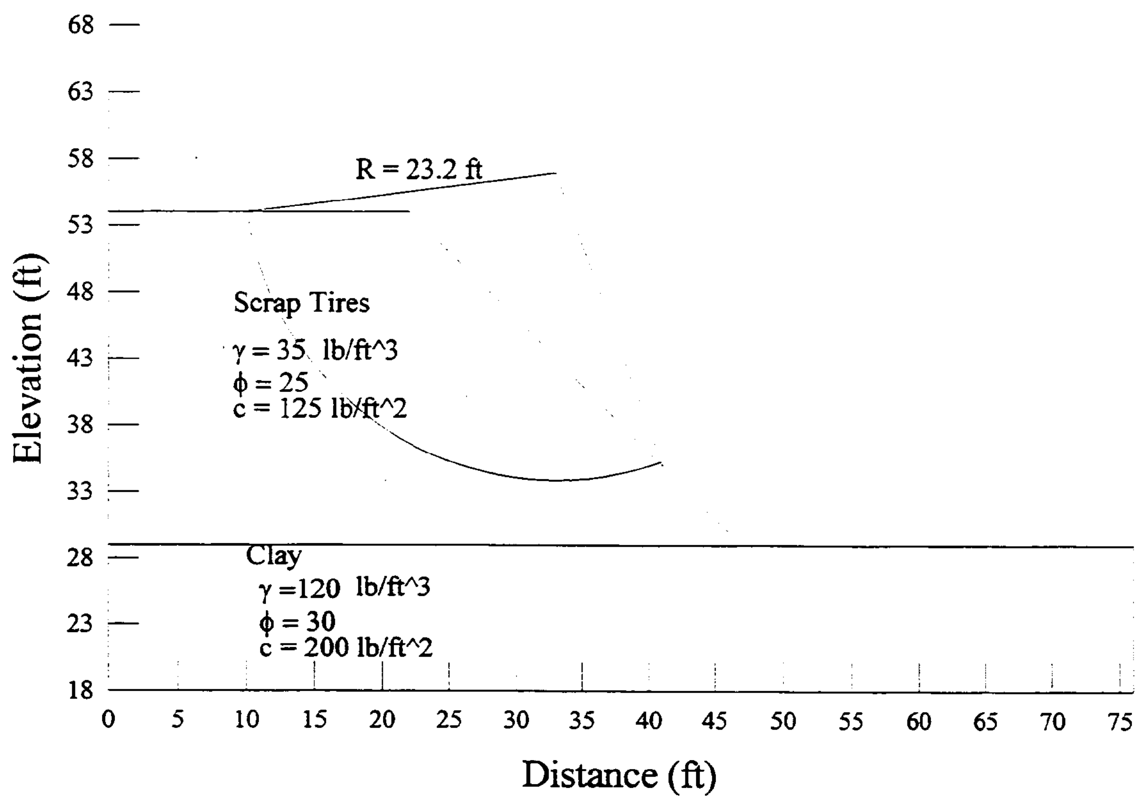


Figure 4.3 Example 2. Scrap Tires Embankment on Clay.

Solution:
Step 1: Draw the figure to scale.
Step 2: Divide the sliding mass into slices as shown in figure 4.4.
Step 3: Set up a spreadsheet as shown in table 4.2.
Step 4: Extract the required values from figure 4.4 and perform the calculations. Scrap tires have a high factor of safety in comparison to the sand layer.

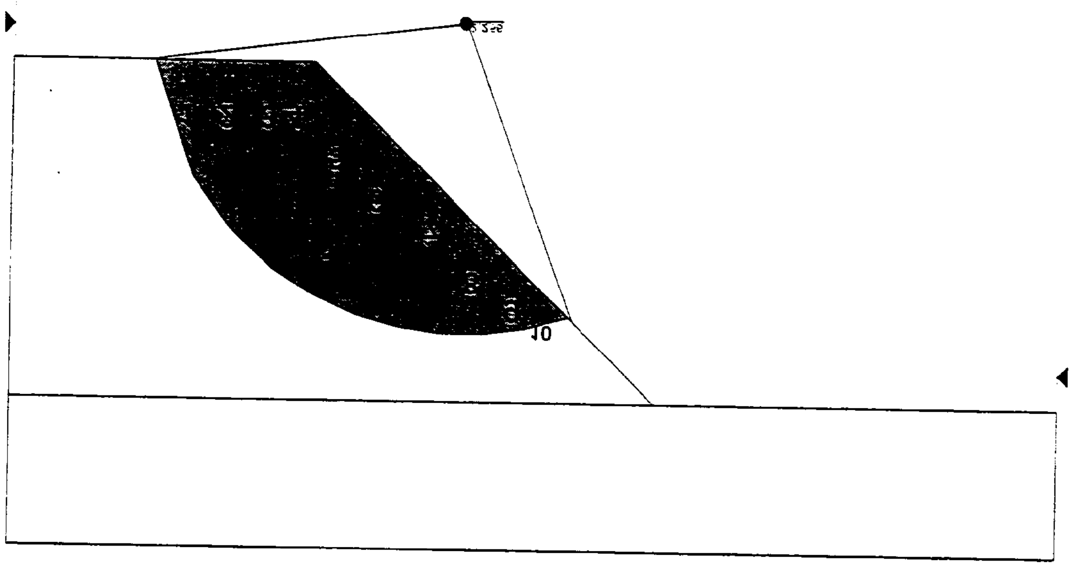


Figure 4.4 Graphical Solution to Example 2.

Table 4.2 Solution to Example 2.

Slice Number	Slice Width b (feet)	Base Length l (feet)	Slice Angle α (°)	m_α	Weight W (lb)	$W \sin\alpha$ (lb)	$\frac{cb}{m_\alpha}$ (lb))	$\frac{W \tan\phi}{m_\alpha}$ (lb)
1	3.0	9.1	71.1	0.52	581.5	550.068	711.1	521.8
2	3.0	5.0	53.5	0.76	1122.5	901.9679	485.4	687.5
3	3.0	4.0	42.3	0.88	1457.0	980.5228	420.5	773.1
4	3.0	3.5	32.9	0.95	1691.4	919.4687	388.3	828.7
5	3.1	3.4	24.3	1.00	1792.9	737.3478	390.9	839.0
6	3.1	3.2	16.0	1.02	1577.2	434.4442	382.5	722.3
7	3.1	3.1	8.0	1.02	1309.5	182.9895	382.2	599.2
8	3.1	3.1	0.2	1.00	994.1	-4.04534	389.8	464.0
9	3.1	3.1	-7.6	0.96	632.6	-83.2462	404.0	305.9
10	3.1	3.2	-15.5	0.91	223.5	-59.7455	428.8	114.7
				SUM	11382.2	4559.8	4383.5	5856.2

Using equation 3.11, the factor of safety is determined as follows:

$$F_s = \frac{\sum_{n=1}^{n=10} \frac{cb + W\tan\phi}{m_\alpha}}{\sum_{n=1}^{n=10} W\sin\alpha} = \frac{4383.5 + 5856.2}{4559.8} = 2.25$$

4.3 EXAMPLE 3

Determine the factor of safety of the slope composed of layers of soil and tire shreds shown in figure 4.5 using the simplified Bishop method.

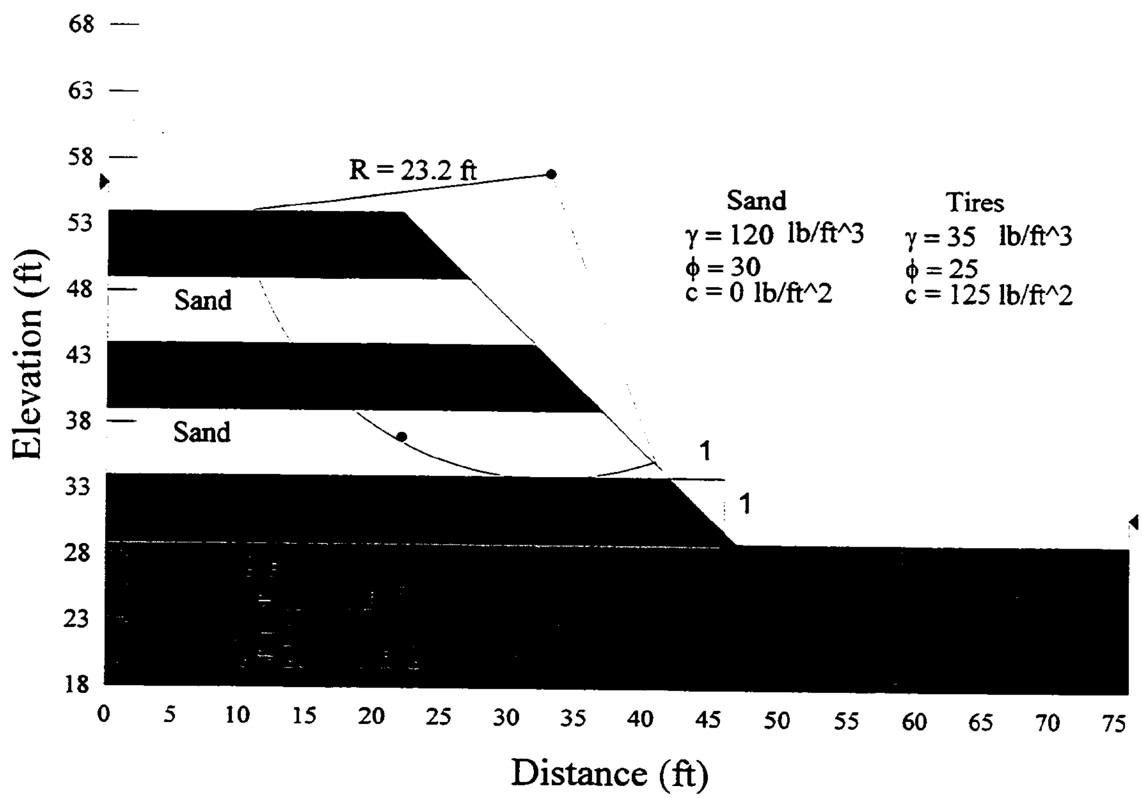


Figure 4.5 Example 3.Layers of Soils and Scrap Tires Embankment on Clay.

Solution.

Step 1: Draw the figure to scale.
Step 2: Divide the sliding mass into s 4.6.
Step 3: Set up a spreadsheet as shown in table 4.3.
Step 4: Extract the required values and perform the calculations. Slices 1, 3, and 4 are contained in the scrap tire layer, where all other slip surfaces are contained in the sand layer. Use the appropriate value of ϕ_{cr} and c_{cr} at the base of each slice. For example, $\phi_{cr} = 30°$ and $c_{cr} = 125\text{-lb/ft}^2$ for scrap tires are applicable to the bases of slices 1, 3, and 4, while $\phi_{cr} = 30°$ and $c_{cr} = 0$ lb/ft^2 for scrap tires are applicable to the bases of slices 2, and 5-12.

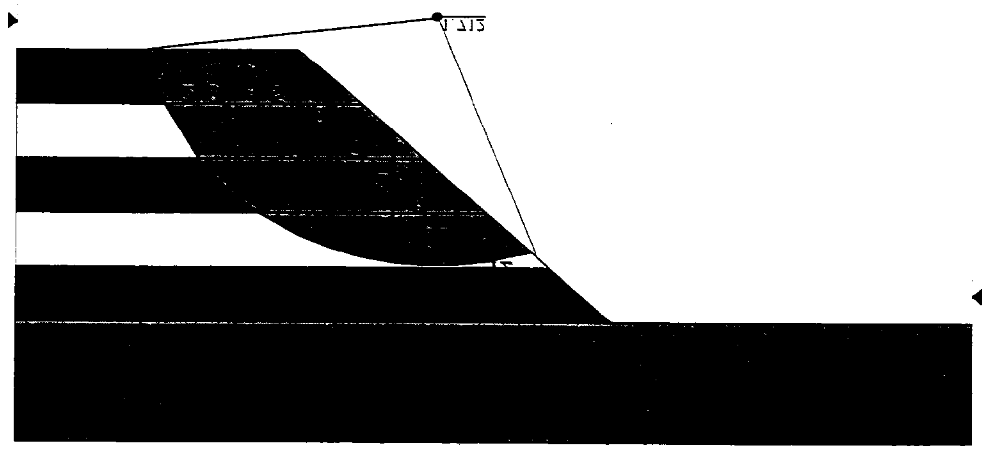


Figure 4.6 Graphical Solution to Example 3.

Table 4.3 Solution to Example 3.

Slice Number	Slice Width b (feet)	Base Length l (feet)	Slice Angle α (°)	m_α	Weight W (lb)	$W \sin\alpha$ (lb)	$\frac{cb}{m_\alpha}$ (lb)	$\frac{W \tan\phi}{m_\alpha}$ (lb)
1	1.2	5.2	76.0	0.56	134.5	130.4	1271.3	123.7
2	2.6	5.6	62.4	0.75	1359.5	1204.6	0.0	1029.5
3	2.4	3.7	50.6	0.88	1960.2	1514.8	867.6	1081.5
4	2.4	3.2	41.9	0.96	2163.2	1445.7	576.5	1089.4
5	3.0	3.6	33.4	1.01	3279.8	1804.4	0.0	1855.4
6	2.5	2.8	25.3	1.04	3057.1	1308.3	0.0	1684.0
7	2.5	2.6	18.6	1.05	3139.9	999.0	0.0	1717.8
8	2.5	2.6	12.0	1.05	2860.2	596.1	0.0	1575.2
9	2.5	2.5	5.7	1.03	2226.8	219.8	0.0	1250.1
10	2.5	2.5	0.6	1.00	1775.3	19.5	0.0	1028.8
11	2.5	2.5	-6.9	1.03	1507.1	-181.8	0.0	914.0
12	3.5	3.7	-14.7	0.56	983.1	-249.4	0.0	643.7
				SUM	24446.7	8811.4	6162.8	11686.3

Using equation 3.12, the factor of safety is determined as follows:

$$F_s = \frac{\sum_{n=1}^{n=12} \frac{cb + W\tan\phi}{m_\alpha}}{\sum_{n=1}^{n=12} W\sin\alpha} = \frac{2715.4 + 12435.5}{8811.4} = 1.71$$

In reviewing examples 1-3, for the same radius of failure, the sand configuration had the lowest factor of safety, and the scrap tire configuration had the highest factor of safety. The low unit weight of scrap tires improved the factor of safety of the embankment and lowered the resisting and sliding forces in the embankment. Unlike a typical sand, scrap tires exhibit cohesion which also will improve the stability of a slope. Note that the scrap tires in these examples were assumed to be compacted loosely. There should be a corresponding increase in shear strength as the tires are compacted.

4.4 PARAMETRIC ANALYSIS

In this portion of the study, a parametric analysis was conducted to compare the slope stability of sand, tire shreds, and layered system. The analysis was conducted by varying the slope angle and slope height. The layered system consisted of alternating 5-ft layers of sand and scrap tires. In addition, the three configurations were analyzed with and without a 5-ft soil cover. These configurations were analyzed with the embankment above the water table. Table 4.4 lists the soil parameters, slope angles, slope heights, and soil cover heights that were analyzed.

Figure 4.7 shows the results of the parametric analysis for minimum factor of safety versus the slope height for sand, tires, and layered system for the uncapped slope. Figure 4.7 also shows a comparison of the minimum factor of safety and the slope angle for the three systems. In general, sand and the layered systems exhibit similar trends in the minimum factor of safety. The low factor of safety for these systems may be attributed to localized failures in the slope, which is caused by the lack of cohesion of the sand layer. The tire system shows an increase in the factor of safety as the slope height decreases. As the slope angle decreases, the factor of safety increases.

Figure 4.8 shows the results of the parametric analysis for minimum factor of safety versus the slope height for sand, tires, and layered system for capped slope. Figure 4.8 also shows a comparison of the minimum factor of safety and the slope angle for the three systems. In general, the three systems exhibit similar trends in the minimum factor of safety, where as the slope angle increases, the minimum factor of safety decreases. The sand configuration has the lowest factor of safety. In designing a layered system, as the tire height increases and/or as the sand layer height decreases, the factor of safety increases.

Table 4.4 Soil and Slope Properties

Slope Height (ft)	**Slope Angle (°)**		**Soil Cover Height (ft)**
10	26.6		0
20	33.7		5
25	38.7		
30	45		
35			
45			
Soil Parameter			
Soil	**Unit Weight (lb/ft^3)**	**Angle of Friction (°)**	**Shear Strength (lb/ft^2)**
Sand	120	30	0
Tire Shreds	35	25	125
Clay	120	30	200

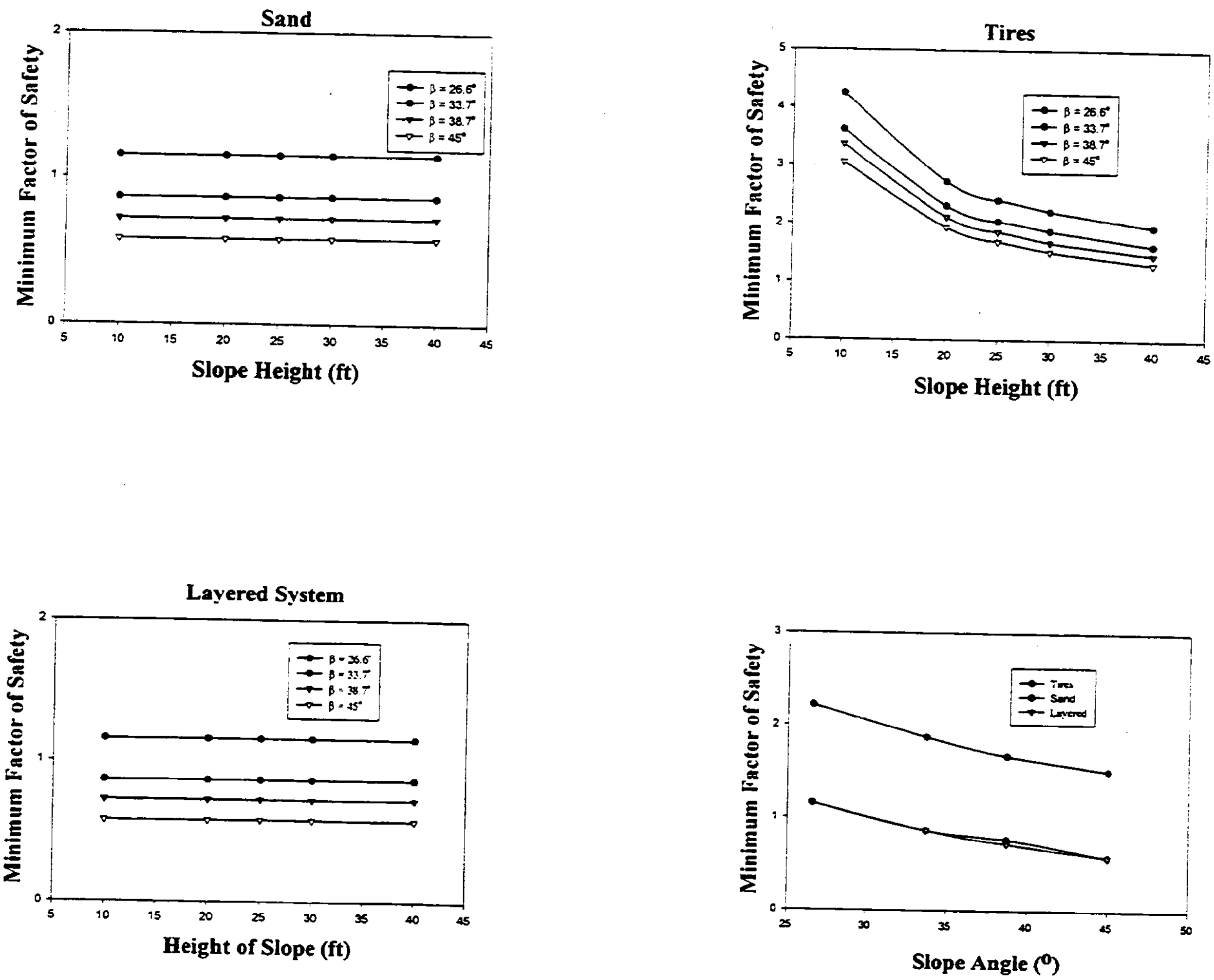


Figure 4.7 Parametric Analysis of Uncapped Slopes

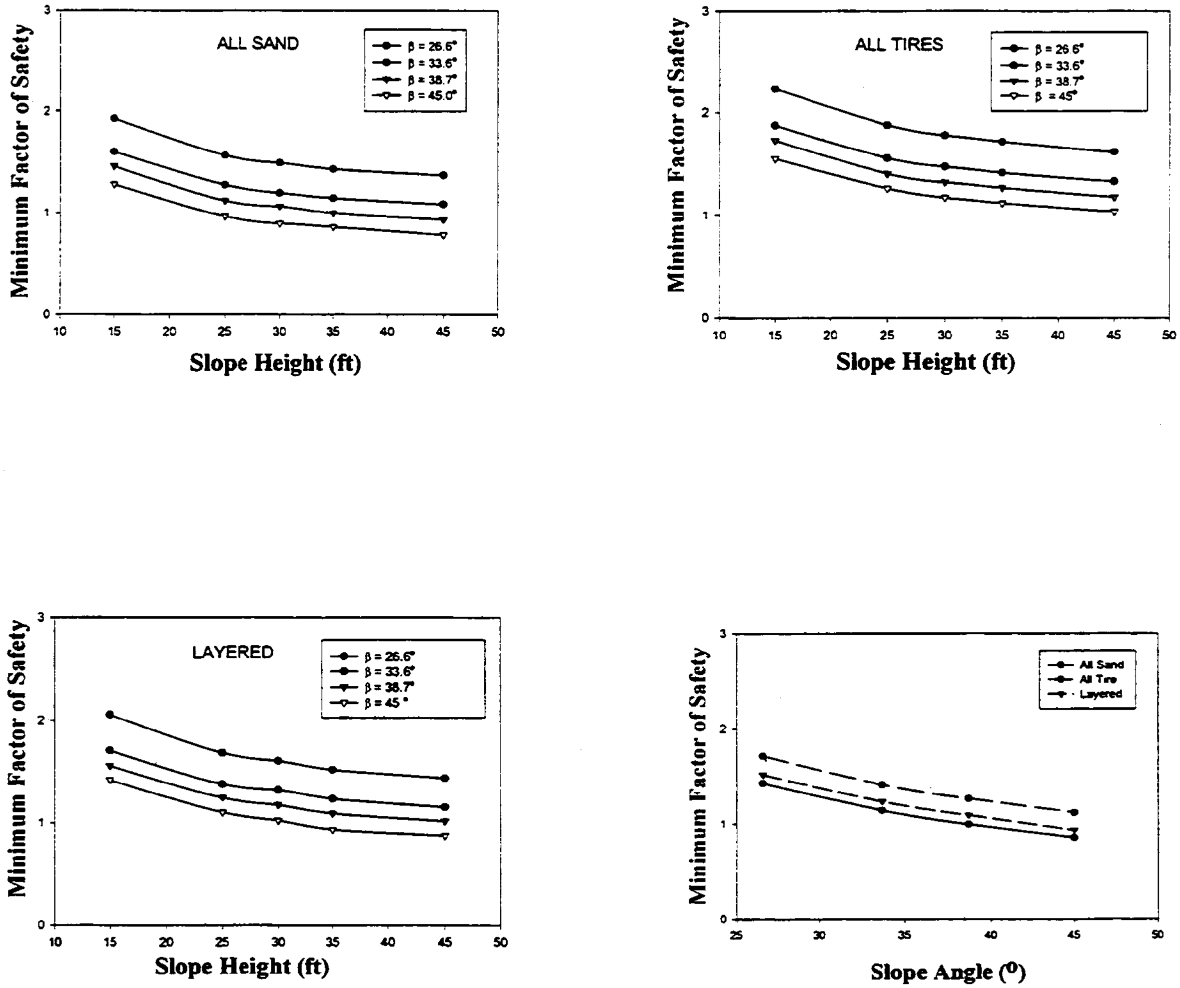


Figure 4.8 Parametric Analysis of Capped Slopes

5. LABORATORY TESTING

5.1 OVERVIEW

In this portion of the document, laboratory testing was conducted to determine the physical and chemical properties of tire shreds (i.e., 1 to 6 inches). Previous research on the physical and chemical properties of scrap tires has focused on tire chips, since most standard laboratory equipment can be easily modified for tire chips. The impetus of this study was to determine the physical and chemical properties of tire shreds to aid the state of Pennsylvania in developing specification standard.

Physical testing was conducted to assess the performance of tire shreds as embankment material. The properties that were tested include water absorption, specific gravity, permeability, gradation, exposed wires, compaction, compression, and shear strength. Chemical testing was conducted to assess the potential for tire shreds to leach deleterious materials. Continuous flow column test and pulsed flow column tests were conducted to analyze the leachate generated from the scrap tires. Chemical analysis was conducted to determine the pH, turbidity, TOC, iron, lead, and chromium levels of the leachate generated from the columns. To assess the potential occurrence of exothermic reactions, thermo gravimetric analysis (TGA) was also performed on the scrap tires. TGA is a thermal analysis technique used to measure changes in the weight (mass) of a sample as a function of temperature and/or time. TGA is commonly used to determine degradation temperatures, residual solvent levels, absorbed moisture content, and the amount of inorganic (noncombustible) filler in material compositions.

5.2 MATERIALS

Tire shreds were obtained from Renaissance Recycling in Wind Gap, Pennsylvania, (here in referred to as Wind Gap) where over a half million tires are stockpiled. Renaissance Recycling specializes in the production of crumb rubber and tire-derived fuels (TDF). Scrap tires at the facility include passenger, light truck, medium and heavy off road vehicles. In general, scrap tires from the facility are a mixture of steel, fiber and fiberglass belts. To obtain the tire shreds, whole tires were passed once through Mac Saturn 7246 hydraulically-driven shredder. To obtain smaller particle sizes, scrap tires are repeatedly passed through the shredder. In this study, 2 cubic yards (approximately 1,500-lb) of tire shreds were obtained from Renaissance Recycling.

5.3 EQUIPMENT

5.3.1 Chemical Analysis

For pH determination, an Orion meter model 410A and pH probes were utilized. The turbidity was measured using a Hach 2100AW turbidimeter. Iron, lead, and chromium were measured on a Hach model DR4000 spectrophotometer. The total organic carbon was measured using a Dohrman DC-180 Carbon analyzer.

5.3.2 Large Scale Direct Shear Apparatus

Conventional direct shear testing devices are typically 3 inches in diameter or 2 inches in length and width, which is not suitable for testing tire shreds. In order to test for the shear strength parameters of tire shreds, the minimum aspect ratio of the apparatus to the maximum particle size should be 2 to 1. In this study, a large-scale direct shear apparatus was built with a length and width of 24 inches (61-cm). The shear box measures 12 inches (30.5-cm) in overall height with the upper and lower portions of the box each measuring 6 inches (15.25-cm). The shear box was fabricated with aluminum. The shear device provides a means of applying a normal stress to the faces of the specimen, for measuring change in thickness of the specimen. The device is capable of applying a shear force to the specimen along a predetermined shear plane parallel to the faces of the specimen. Figure 5.1 shows a schematic diagram of the shear box. Figure 5.2 shows a photograph of the direct shear box apparatus.

The normal force was applied using a 300 kips. capacity universal testing machine. The testing machine is calibrated annually to an accuracy of plus or minus one percent. To shear the specimen, a Rexroth power unit and a series of Enerpac™ hydraulic jacks were utilized. The device is capable of shearing the specimen at a uniform rate of displacement, with less than 5 percent deviation, and permits adjustment of the rate of displacement from 0.01 to 0.1 mm/min. The shearing rate was usually maintained through the adjustment of the hydraulic pump and a load cell determined the shear force.

The shear force is measured using a load cell, which is comprised of a 3.5-inch outer diameter by 3.38-inch inner diameter by 3- inch long hollow aluminum cylinder with electric resistance strain gages bonded to its periphery. The load cell was calibrated in a testing machine to correlate the strain in load cell to the force on the load cell. Figure 5.3 shows the load cell calibration curve was utilized in the experiments to convert a voltage experienced by the load cell to a specific load in pounds or kilograms. This effectively enables a direct readout from the cell and a determination of the appropriate load applied.

The horizontal displacement of the lower portion of the box and the vertical displacement of the upper box caused by the normal load were measured using conventional dial gauges.

5.3.3 Column Test

Column tests were conducted using a 12-in diameter by 3-ft in height column. The columns were composed of clear PVC. Rainwater was circulated through the column using a peristaltic pump. Figure 5.3 shows a schematic diagram of the column test. Figure 5.4 shows a photograph of the column experiment.

5.4 PROCEDURES

Testing of the physical properties of tire shreds followed the American Society of Testing and Materials (ASTM) procedures listed below:

- Absorption- ASTM C 128
- Specific gravity-ASTM C 128
- Permeability-ASTM D 2434
- Gradation-ASTM D 422
- Exposed Wires-ASTM D 6270
- Compaction-ASTM D 698 (60 percent of Standard Test Method) and D 1557 (Modified)
- Compression-ASTM D 2166
- Shear Strength-ASTM D 3080

Modifications to these procedures for tire shreds are noted in ASTM D6270. In this section, modifications for the shear strength and consolidation procedures are also given below.

Testing for the chemical properties of scrap tires follows the Standard Methods for the Examination of Water and Wastewater and are listed as follows:

- pH-ASTM D 4972
- Turbidity-ASTM D 1889
- TOC
- Iron
- Chromium
- Lead

5.4.1 Column Tests

Two-column tests were conducted utilizing tire shreds. At the bottom of the column, a nonwoven geotextile was placed. Two feet (61-cm) of scrap tire was placed above the geotextile. A nonwoven geotextile was placed on top of the scrap tire layer and a 6-in (15.24-cm) layer of silica sand was placed above the geotextile.

The column was filled with rainwater at the beginning of the test. The stopcock at the effluent end of the column was opened to start the tests. Tests were conducted for one week with the peristaltic pump set at a flow rate of 2 ML/s. At the end of the test, approximately 1,210 liters of rainwater passed through the column. Samples were collected twice daily and were tested for pH, TOC, turbidity, iron, lead, and chromium.

At the conclusion of the continuous flow experiments, pause flow experiments were conducted by closing the stopcock at the effluent end of the column and by turning off the peristaltic pump. The rainwater was left into the column, and samples of the leachate were periodically collected and tested by turning the pump on and opening the effluent stopcock.

5.4.2 Shear Strength Test

The compacted specimen was placed into the shear box and attached the shear box to the loading system. The shear force was connected and adjusted loading system so that no force is imposed on the load-measuring device. The horizontal displacement measurement device was properly positioned and adjusted to measure shear displacement. An initial reading was obtained by setting the measurement device to indicate zero displacement. The transfer plate was loaded on the top of the specimen in the shear box.

Three or more specimens were tested, each under a different normal load (750-lb-4,200-lb) to determine the effects upon shear resistance and displacement, and strength properties such as Mohr strength envelopes. The normal force loading yoke was placed into position and was adjusted so the loading bar was horizontal. The dead load lever loading systems was leveled. A ball bearing was placed on the load transfer plate and was adjusted the yoke until the contact was tight.

A normal load was applied to the specimen. The applied vertical load and horizontal loads were recorded on the system. The vertical displacement measurement device was attached and adjusted. Initial readings for the vertical measurement device and for the horizontal displacement measurement device were obtained. The desired normal stress or increment thereof was calculated and recorded. The normal stress was applied by adding the appropriate mass to the lever arm hanger. The specimen was sheared.

The displacement rate was selected and was set (For these tests a rate of 0.05-mm/min was utilized). The initial time, vertical and horizontal displacement, and normal and shear forces was recorded. Data readings of time, vertical and horizontal displacement, and shear force at desired interval of displacement were obtained. Data readings were taken at displacement intervals equal to 0.1-in to accurately define a shear stress-displacement curve. After reaching failure, the test apparatus was stopped. The normal force was removed from the specimen by removing the mass from the lever and hanger. The nominal shear stress versus relative lateral displacement was calculated and plotted.

5.4.3 Compression Test

Large-scale compression tests were conducted using the direct shear apparatus discussed in section 5.3.1. To measure the vertical displacement, dial gauges were utilized. The inside of the container was coated with silicon grease to reduce the friction between the tire chips and the wall of the container. The tire chips were compacted in five layers with 60 percent of Standard Proctor effort.

Load was applied at constant rate of deformation of 13-mm/min (0.5-in/min). Reading from the dial gauge, vertical load, and vertical deformation were taken every 10 seconds. From these readings the vertical stress, the vertical strain were calculated. The maximum load applied was 9,000-lb.

5.5 RESULTS AND DISCUSSION

5.5.1 Physical Testing

Upon initially receiving the tire shreds from Wind Gap, the materials were separated by particle size. Approximately 1,500-lb (337-N) of scrap tires were passed through sieves where half of the materials were comprised of tire chips. Figures 5.6 shows the cumulative particle size distribution of tire chips ranging in sizes from 0-to 50-mm, and figure 5.7 shows the cumulative particle size distribution of tire shreds whose size range varies from 50 to 300-mm. In comparing the Wind Gap tires to figures 2.1a and b, tire shreds and tire chips follow a similar trend to the data presented by Humphrey (2000). From figure 2.1b, the maximum and minimum values for the D_{10} and D_{60} are 30 and 10-mm and 70 and 30 mm, respectively. This corresponds to uniformity coefficient ($C_u = D_{60}/D_{10}$) ranging from a maximum of 7 to a minimum of 1. For tire shreds in Figure 2.1b, the D_{10} and D_{60} range from 70 to 50-mm and 400- to100-mm, respectively, which corresponds to uniformity coefficients ranging from 1.4 to 8. The Wind Gap tire shreds and chips have comparable uniformity coefficients (where $C_u = 2$) to Humphrey's data.

Water adsorption and specific gravity tests were conducted on random samples of tire shreds after the particle size analysis. Three water adsorption and specific gravity tests were conducted at the following size ranges: 25, 50, 100, 200, and 300-mm. The results of water adsorption are shown with the specific gravity in table 5.1. The water adsorption of the tires shreds ranged from 6.7 to 7.0 percent, which are higher than the results reported in table 2.2. The specific gravity of the Wind Gap tire shreds ranged from 1.06 to 1.12, which favorably compare to the results in table 2.2.

The amount of exposed steel belts was measured using procedures outlined in ASTM D6270. Random samples of tire shreds (108 specimens) with steel belts were obtained at different particle sizes. The length and width of the exposed steel belts were measured. The length and width of the rubber tire were also measured. Due to the irregular shape of the tire shreds, the width of the exposed steel belts may be greater than the width of the tire shred. The percentage of exposed wire is obtained by dividing the area of the exposed wire by the area of the rubber and area of exposed wire. Table 5.2 presents the results from measuring the exposed steel belts. For the Wind Gap material, as the tire shreds increase in size, the percentage of exposed steel belts decrease. ASTM D 6270 proposes that tire shreds used in embankments have less than 1 percent by weight of metal fragments, which are at least partially encased in the rubber. Moreover, ASTM D-6270 states that tire shreds with metal fragments encased in rubber should not protrude more than 25.4-mm (1 inch) from the cut edge of tire shreds on 75 percent of the pieces and no more than 50.8-mm (2 inches) on 100 percent of the pieces. The tire shreds from Wind Gap have high percentage of exposed steel. If the tire shreds from Wind Gap are to be utilized in embankments, then a shredder that removes steel belts or a shredder with sharper knives must be utilized. Another alternative for the Wind Gap tire shreds would be to manually separate tires with steel belts.

Compaction tests were performed on tire shreds and tire chips using a 12-inch (30.48-cm) compaction mold with a modified compaction hammer and a 50-lb (222-N) weight dropped 3 feet (91.4-cm). Figure 5.8 shows the modified compaction test performed in the 12-inch compaction mold. Figure 5.9 shows compaction with the 50-lb weight. Three tests were conducted at each tire shred size. The loose density of the tire shreds were determined by pouring the tire shreds into the compaction mold and weighing the mold. Compaction tests were performed using 60 percent of the Standard Proctor compaction energy (7,425-ft-lb/ft^3 (355-kJ/m^3)) using a Modified Proctor hammer and 100 percent of the modified Proctor compaction energy (56,250-ft-lb/ft^3 (2,693-KJ/m^3) using a 50-lb weight. Figure 5.10 shows the test results for the compaction of tire shreds at various particle sizes and the dry maximum unit weight. The loose unit weight of tire shreds compare favorably to the results of previous researchers which range from 21-31 lb/ft^3 (Humphrey, 2000). The modified compaction hammer using 60 percent of compaction energy produced similar results to the 50-b weight using 100 percent of compaction energy. These results are similar to the results presented by Manion and Humphrey (1992), where the compaction energy has only a small effect on the resulting dry unit weight.

Compaction tests were also performed on a 50 percent mix of tire shreds at various particle sizes and silica sand. The dry unit weight of the tire and sand mix was determined in the loose state, at 60 percent of the standard compaction energy, and at 100 percent of the modified compaction energy. Silica sand was tested and has a maximum dry unit weight of 17.5-kN/m^3 and optimum moisture contents of 13.5 percent. Figure 5.11 shows the compaction curves for the 50 percent mix of tire shreds at different particle sizes and sand. As the compaction energy increases, the dry unit weight increases. These results compare favorably to the results of other researchers (Ahmed, 1993; Edil and Bosscher, 1994). As the percentage of soil increases, it can be expected that the unit weight of the mixture also increases.

Hydraulic conductivity tests were conducted on tire shreds to determine how the hydraulic conductivity of tire shreds change as the particle size increases. In this test, a large constant head permeameters test was conducted with a permeameters with a diameter of 12 inches (30.44-cm) and a height of 3 feet (91.2-cm). Samples were compacted to corresponding dry unit weight for a given particles size in figure 5.10 using the modified compaction hammer. Figure 5.12 shows the test results for the hydraulic conductivity and tire shred size. As the tire shred increases in size, the hydraulic conductivity increases. These results compare favorably to the results of previous researchers who obtain hydraulic conductivity values for tire shreds ranging from 0.58 to 23.5-cm/s (Edil and Bosscher, 1994).

Direct shear tests were conducted on scrap tires at various particle sizes. To calibrate the direct shear box, initial tests were conducted on silica sand to determine the Mohr-Coulomb failure envelope. The silica sand was loosely compacted into the shear box at a unit weight of 16.34-N/m^3 (104-lb/ft^3). The angle of friction for the dry silica sand was 34°, which corresponds favorably to literature results (Das, 2000). The primary goal of conducting these tests was to determine how the shear strength varied with particle size. The design of the shear box is such that failure will be constrained along a thin horizontal zone between the top and bottom half of the shear box. In order to get both the peak and critical shear force, the test was conducted under a controlled displacement rate. For each test, the displacement rate was set at 0.05-mm/min, which is within ASTM guidelines for the displacement rate of a shear test (ASTM range is 0.01-0.1-mm/min). Previous researchers (Humphrey, et al., 1992,1993, Humphrey and Sandford, 1993, and Cosgrove, 1995) have conducted direct shear testing on tire chips. However, there is minimal data that exists on tire shreds. Samples were compacted to corresponding dry unit weight for a given particles size in figure 5.10 using the modified compaction hammer. Figure 5.13 shows the Mohr Coulomb failure envelopes for scrap tires at various particle sizes, and table 5.3 shows the corresponding shear strength parameters for the various particle sizes. In general, as the particle size increases, the shear strength of the scrap tires increases. However, note that particle sizes ranging from 50-100-mm had the highest shear strength parameters. This may be a result of the increased affect of the steel belts and wires in creating interlocking forces during the shear test. The increased shear strength parameters for tire shreds at the 50-100-mm particle size may also be a result of the increased dry density. From figure 5.10, note that scrap tires with particles sizes ranging from 50-100-mm (i.e., 75-mm) have the maximum dry density. Figure 5.14 illustrates typical horizontal displacement and vertical stress relationships for tests conducted on scrap tires with particle size ranges of 100-200-mm. Shear strength tests were conducted until there was a decrease in the shear force or until a predetermined horizontal travel distance was reached (i.e., for these tests, that limit was 10 percent of the length of the apparatus). As the vertical load increased from test 1-3 as shown in figure 5.14, the shear stress and horizontal displacement increased.

Compressibility tests were conducted on scrap tires at various sizes, and on tire shreds mixed with soil at different mix ratios. The primary reasons for conducting these tests were:

- To determine the settlement that will occur during construction in the first couple of months and enable an adequate design that accounts for this settlement.
- To enable the determination of deflections caused by live or temporary loads post-construction.
- To determine the in-place unit weight of compressed scrap tire.

Tire shred samples were compacted to corresponding dry unit weight for a given particles size in figure 5.10 using the modified compaction hammer. Figure 5.15 plots the compression test results for tire shreds at various size ranges. As the tire shred size increases, the compressibility increases. This may be a result of the increased voids created by using larger tire shreds. Various researchers, (Manion and Humphrey, 1992; Edil and Boscher, 1992, 1994; Ahmed, 1993; and Ahmed and Lovell, 1993) have measured the compressibility of various mixtures of scrap tires and soil. The general trend is that the compressibility decreases as the percent scrap tire in the mix decreases (Humphrey, 2000).

5.5.2 Chemical Testing

Shredded tires were placed in a container of tap water at a pH of 7.95. Twenty-four hours after the placement of the shredded tires, the pH was 6.98, which results a little more acidic condition. TOC, and turbidity were also measured. Total organic carbon (TOC) determines the degree of organic contamination. A carbon analyzer using an infrared detection system is used to measure total organic carbon. In this procedure, organic carbon is oxidized to carbon dioxide. Suspended matter, such as clay, silt, finely divided organic and inorganic matter, soluble colored organic compounds, and microorganisms, causes turbidity in water. TOC, pH, and turbidity results are shown in table 5.4 as a function of the tire size.

Continuous flow column tests were conducted for seven days. Two columns were utilized with different ranges of scrap tires. Column 1 had scrap tires with a size range from 50-100-mm, and column 2 had a particle size range of 100-200-mm. Three samples were taken each day (8 a.m., 12 p.m., and 4 p.m.) from each column. The effluent collected from the continuous flow column test was measured for iron, lead, chromium, pH, turbidity and total organic content. Figures 5.16a-d illustrate the results for iron, lead, chromium, pH, turbidity, and TOC. Column 1 and 2 gave similar results. Thus, the results are plotted as a single curve. As the rainwater flowed through the column, the concentration of heavy metals decreased. Moreover, the turbidity and TOC concentration also decreased as the rainwater flowed through the column. The pH of the column initially increased and then decreased with time. The initial increase in the pH may be a result of organic and inorganic debris on the tires. As the metals and turbidity were being washed from the column, the pH raised back to near the initial value for the influent water of 6.0. The continuous flow experiments simulate the free drainage condition that may occur in an embankment or behind a retaining wall, which is built above the water table, where scrap tires are utilized as backfill. If water is allowed to drain freely through the scrap tire fill, the water quality of the effluent from the tire shreds will improve with time. Humphrey et al. (1997b) conducted a five-year study on the effect of tire shreds placed above the water table and determined that the effects of using recycled tires on groundwater were negligible. Continuous flow column experiments support the conclusions rendered by the Humphrey et al. study, where the rainwater that passes through the tire fill will act to clean the tires.

Pause flow column experiments were conducted on column 1 and will continue to be conducted for one year. In the pulse flow experiment, the effluent stopcock is closed and the peristaltic pump is turned off. The pause flow experiment simulate a worst case scenario where a scrap tires are utilized to build an embankment below the water table or utilized as backfill below the water table. Figures 5.17a-d illustrates the results for iron, lead, chromium, pH, turbidity, and TOC. The concentration of heavy metals increased with time. The increase in heavy metal concentration is expected since 30 percent of the scrap tires placed into the column contained steel belts. The increase in iron may also be caused by the oxidation of iron and by the precipitation of rust (i.e., redox reactions). Rusting is essentially a process of oxidation in which iron combines with water and oxygen to form rust, the reddish-brown crust that forms on the surface of the iron. Rust, a chemical compound, is a hydrated ferric oxide, $Fe_2O_3 \cdot nH_2O$. The turbidity of the effluent increased with time. The increase in turbidity may be attributed to the precipitation of rust. In addition, the TOC of the effluent increased with time. This increase in TOC may be attributed to microbial colonies that may have been present on the tires and began to multiply as the rainwater resides in the column.

The rate of oxidation of Fe^{2+} by O_2 in water is given by (Singer and Stumm, 1970):

$$\frac{dm_{Fe^{2+}}}{dt} = -(2.91e^{-9} + 1.33e^{12}(\alpha_{OH})^2 P_{o_2})m_{Fe^{2+}}$$

where t is time in seconds, α_{OH} is the activity of the hydroxyl ion, m_{Fe}^{2+} is the total molality of ferrous iron in solution, and P_{O2} is the oxygen partial pressure (atm). It can be seen that the pH rapidly decreases at the beginning of the reaction. From the kinetic equation shown above, it can also be postulated that the slope of Fe^{2+} against time is initially very steep, but lessens as the reaction progresses. When the experiment was performed in reality in the unbuffered solution, it is noted that the pH began to rise. This rise in pH is consistent with slowly forming hydroxy-complexes of Fe^{3+}. Because the oxidation reaction by itself consumes protons, the pH would rise if the hydroxy-complexes that lower the pH form slowly.

5.4.3 TGA Analysis

In order to determine the thermal stability of scrap tires in air, a technique known as thermo gravimetric analysis (TGA) was utilized. The results showed that scrap tires are generally stable up to 200°C. Figure 5.18 shows the TGA derivative weight curves and Figure 5.19 shows the TGA weight curves with end point weight loss. An additional experiment in isothermal mode was conducted to determine the thermal stability of the scrap tires in air at 250°C. The results are presented in figure 5.20.

In Figure 5.18, the corresponding peaks show the temperature of thermal processes such as evaporation, gasification, and decomposition. It seems that the stability of the stripped sample (rubber only), which was taken from a cross section is slightly worse than that of the stability of the scrap tires containing fibers. This difference is quite small, however, and is approximately only 10°C. On the other hand considering the peak area or comparing figure 5.19, it seems that the sample with fibers lost more weight, suggesting that some components of the rubber evaporates first, but the majority of it is more stable. The fibers in the rubber matrix have good stability up to 311°C, but then a sudden decomposition begins which involves large parts of fiber. In the analysis of the sample with steel wire, the fact that the steel has a large contribution to the total sample weight must be taken into consideration. This would explain the greater stability in comparison to the others. Additionally, the density in this case was higher such that the sample weight was 50-mg versus 12-mg for the sample with fibers and 28-mg without.

The isothermal study of tire sample without fibers showed good thermal stability at 250°C. Figure 5.20 shows that only 8.8 percent of the weight was lost after one hour at 250°C in the air. Additionally, from the shape of the weight curve it can be found that the decomposition or evaporation process is slowing down and extrapolation predicts that the loss will not be greater than 10 percent. In conclusions, these results show that the scrap tires are stable in air up to 200°C and even at higher temperatures (250°C) in air the weight loss is less than 10 percent.

Table 5.1 TOC, pH, and Turbidity Results.

Tire Size (mm)	TOC(ppm)	PH	Turbidity (NTU)
<50	22.675	6.97	234
50-100	17.43	6.98	202
100-200	14.514	6.96	251
200-300	3.064	6.95	99

Table 5.2 Specific Gravity and Water Adsorption Results.

Tire Size (mm)	Specific Gravity	Water Adsorption (%)
<50	1.11	6.7
50-100	1.1	6.95
100-200	1.06	7.1
200-300	1.1	7.0

Table 5.3 Exposed Steel Belts.

Average Rubber Length (mm)	Average Rubber Width (mm)	Average Tire Area (mm^2)	Samples	Average Length of Wire (mm)	Average Width of Wire (mm)	Average Area of Wire (mm^2)	Wire in the Shred (%)
25	25	625	30	8.3	20	166	21.0
75	29	2167	30	7.33	25	183	7.8
150	29	4333	20	1.3	32	41.6	1.0
250	40	10000	17	16.47	35	576	5.5
400	26	10400	11	13	40	520	4.8

Table 5.4 Angle of Friction and Cohesion of Tire Shreds at Various Sizes.

Tire Size (mm)	Angle of Friction	Cohesion (lb/ft^2)
<50	15	265
50-100	32	251
100-200	27	251
200-300	29	235

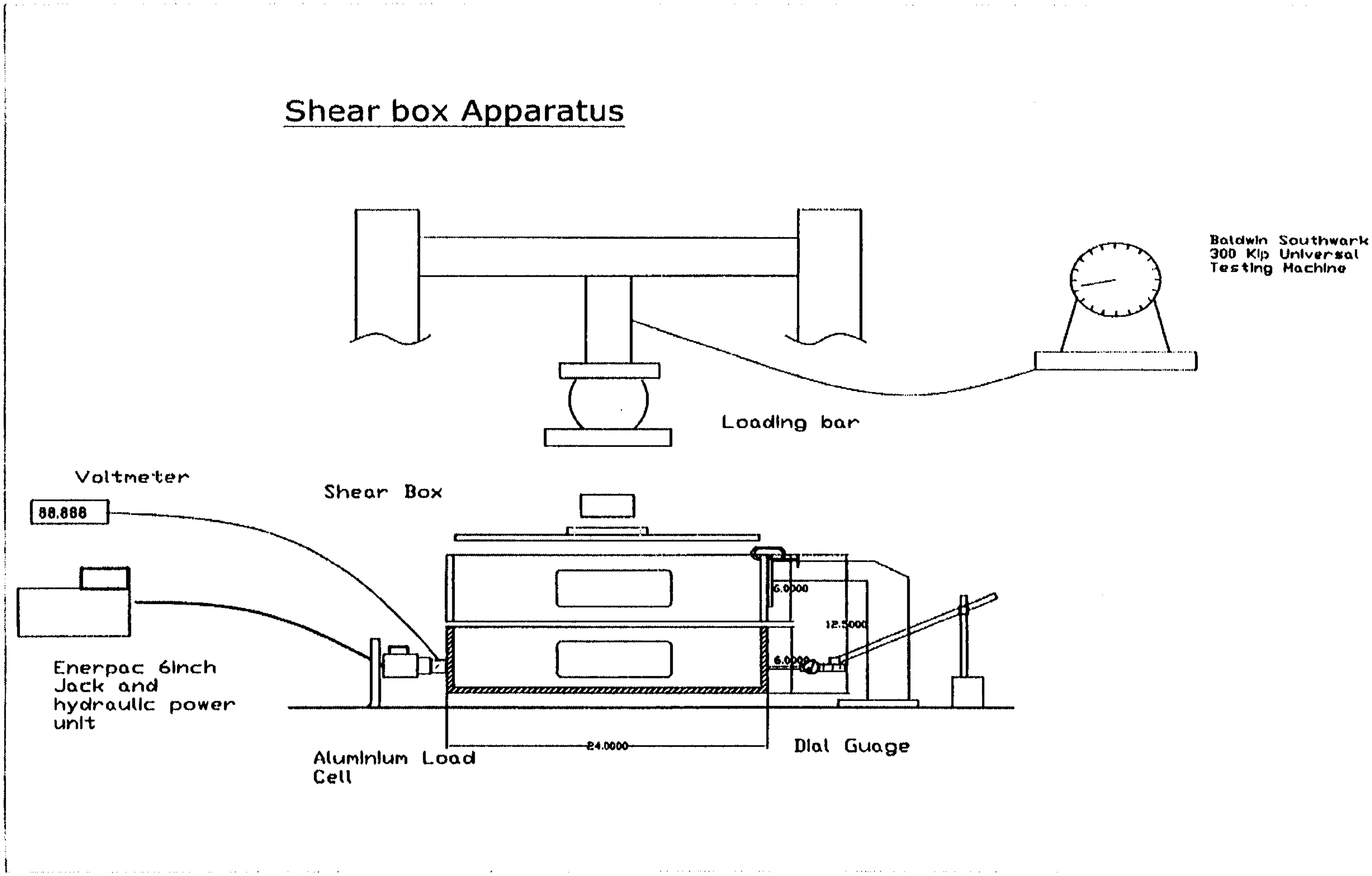


Figure 5.1 Schematic Diagram of Direct Shear Box.

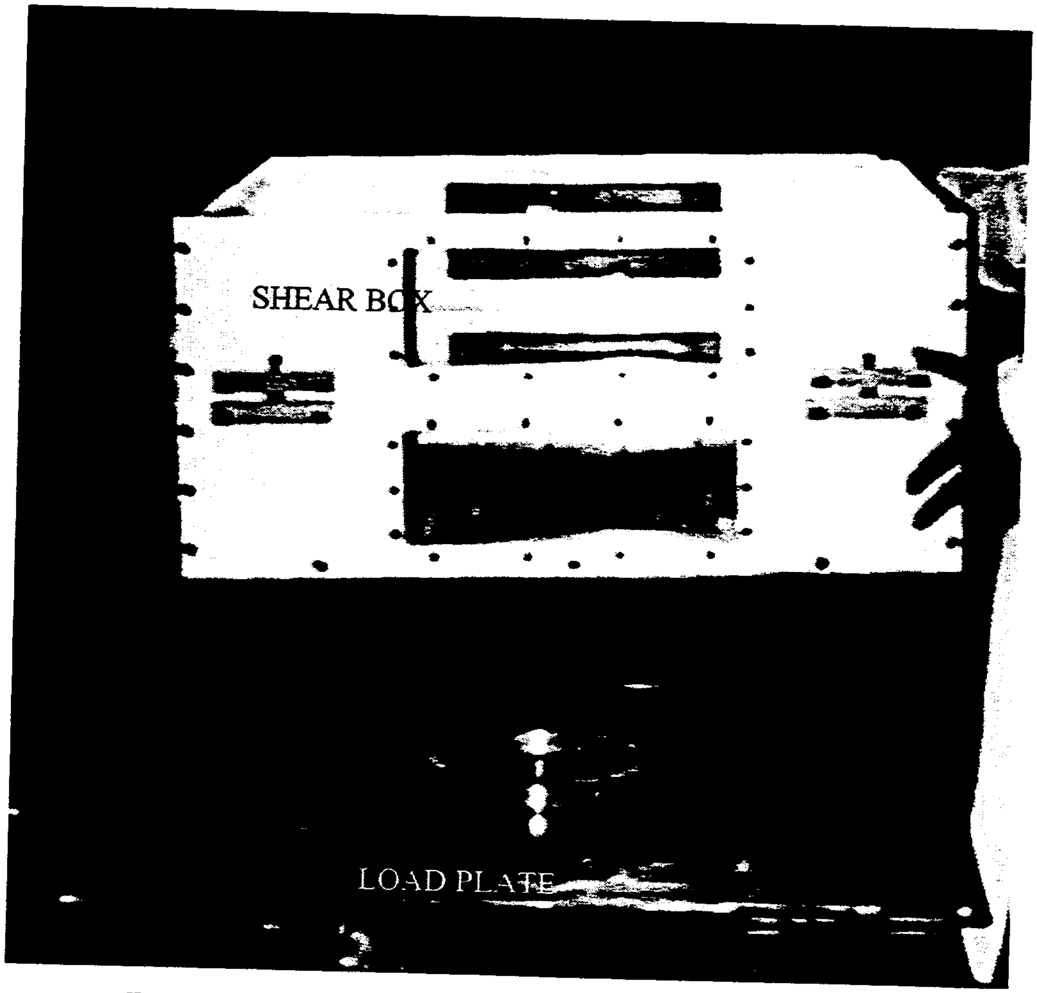


Figure 5.2 Photograph of the Direct Shear Box Apparatus.

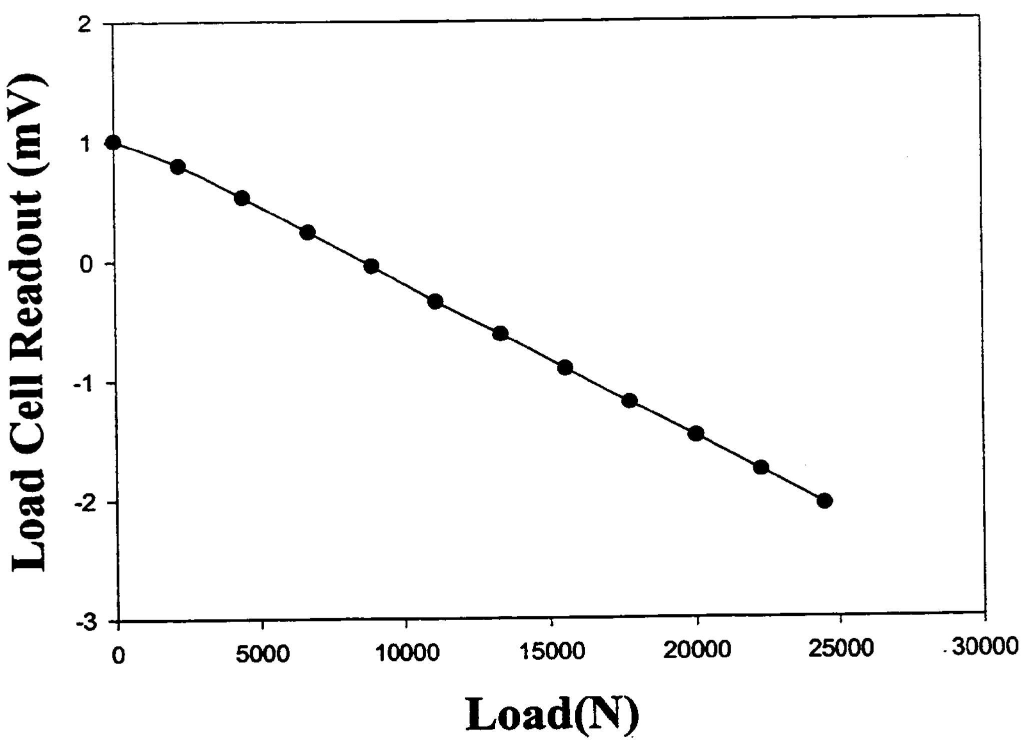


Figure 5.3 Load Cell Calibration Curve.

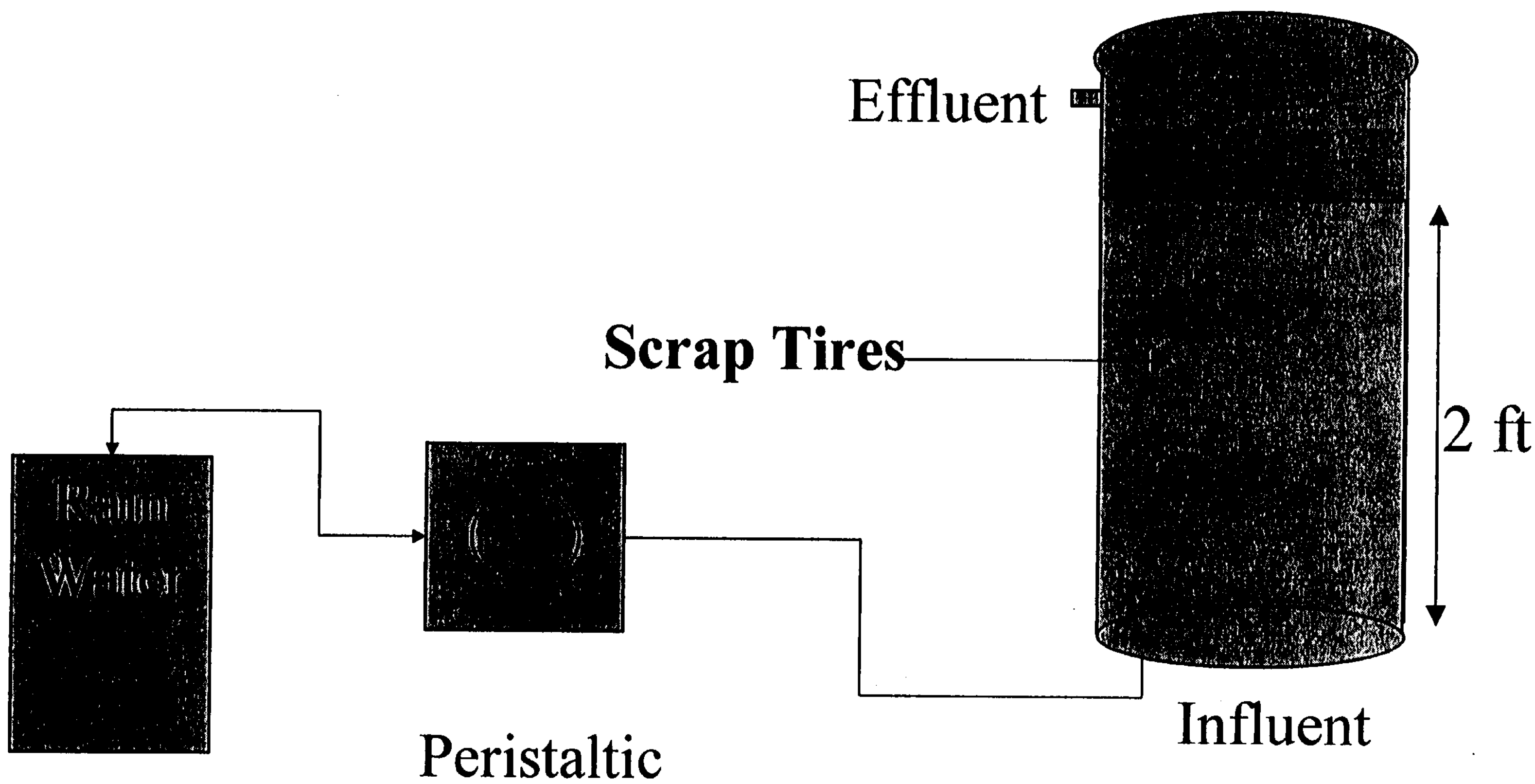


Figure 5.4 Schematic Diagram of the Column Test.

Figure 5.5 Photograph of the Column Experiment.

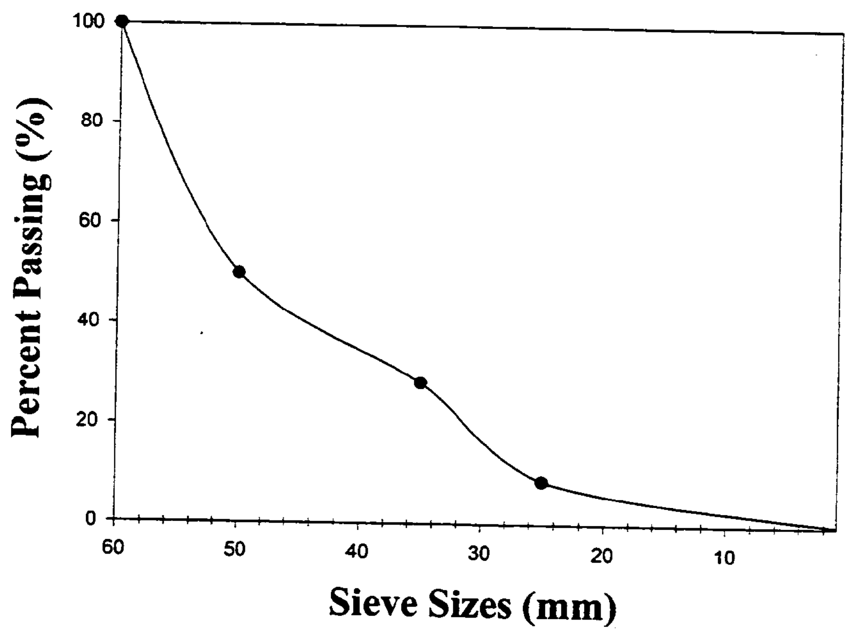


Figure 5.6 Particle Size Analysis of Tire Chips.

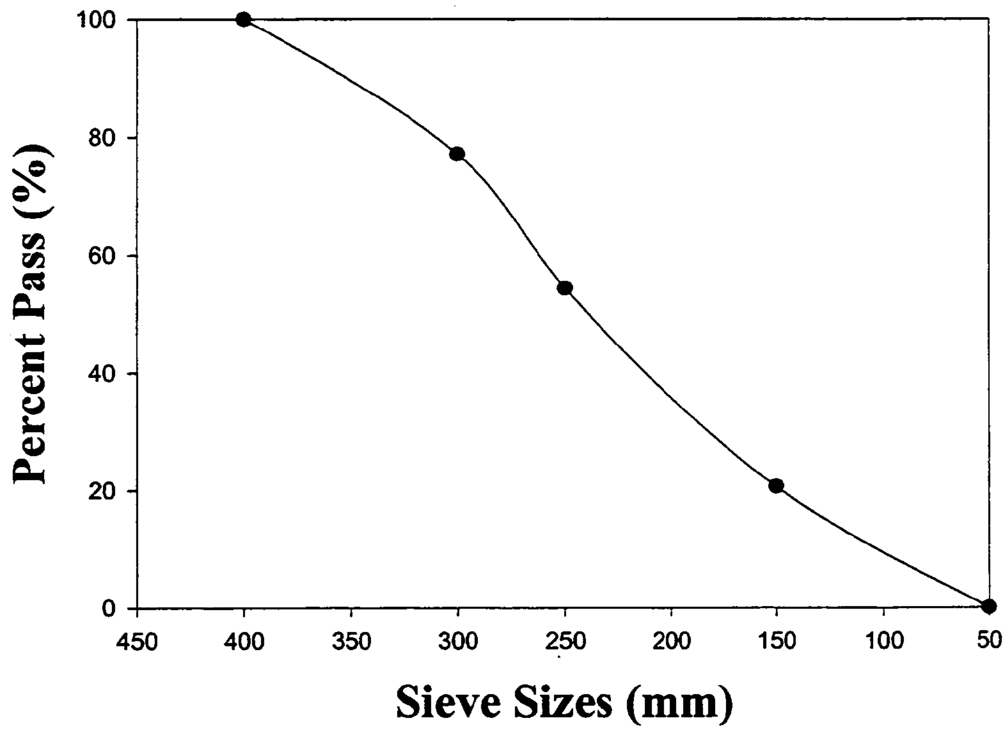


Figure 5.7 Particle Size Analysis of Tire Shreds.

Figure 5.8 Modified Compaction Test.

Figure 5.9 50-lb Hammer Compaction Test.

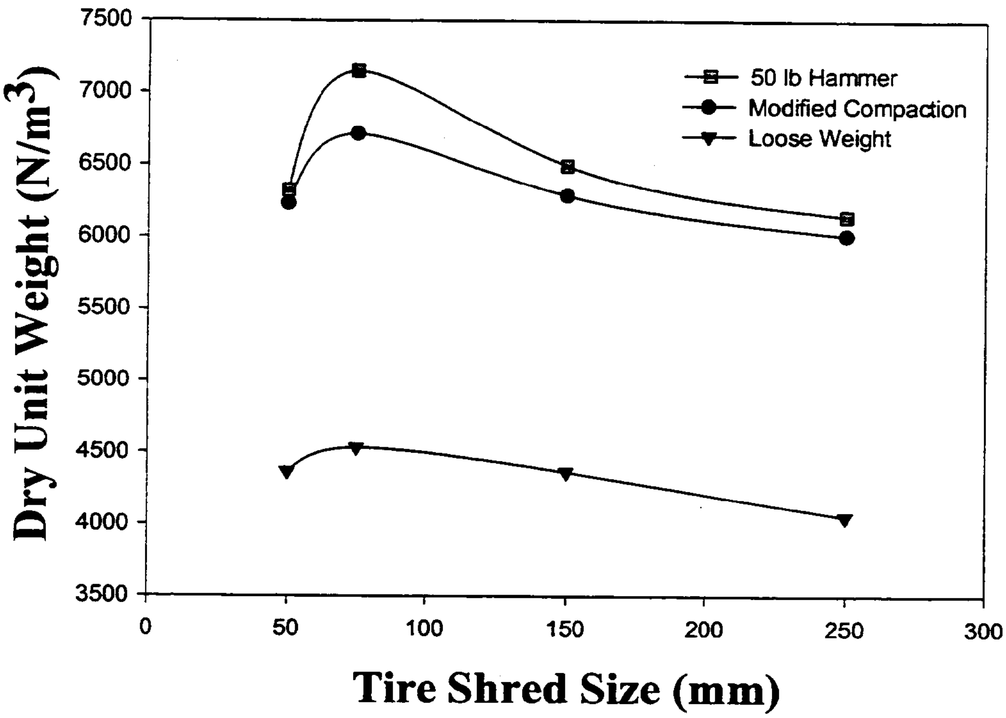


Figure 5.10 Compaction Test Results on Tire Shreds.

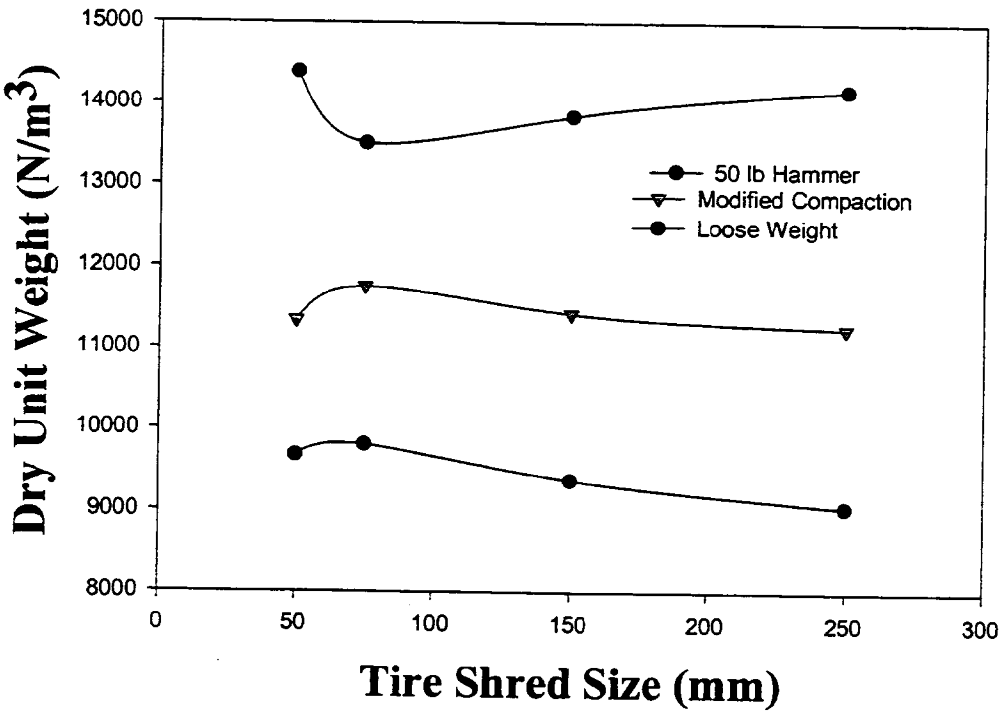


Figure 5.11 Compaction Results on Tire Shreds/Soil Mixture 50/50 by Volume.

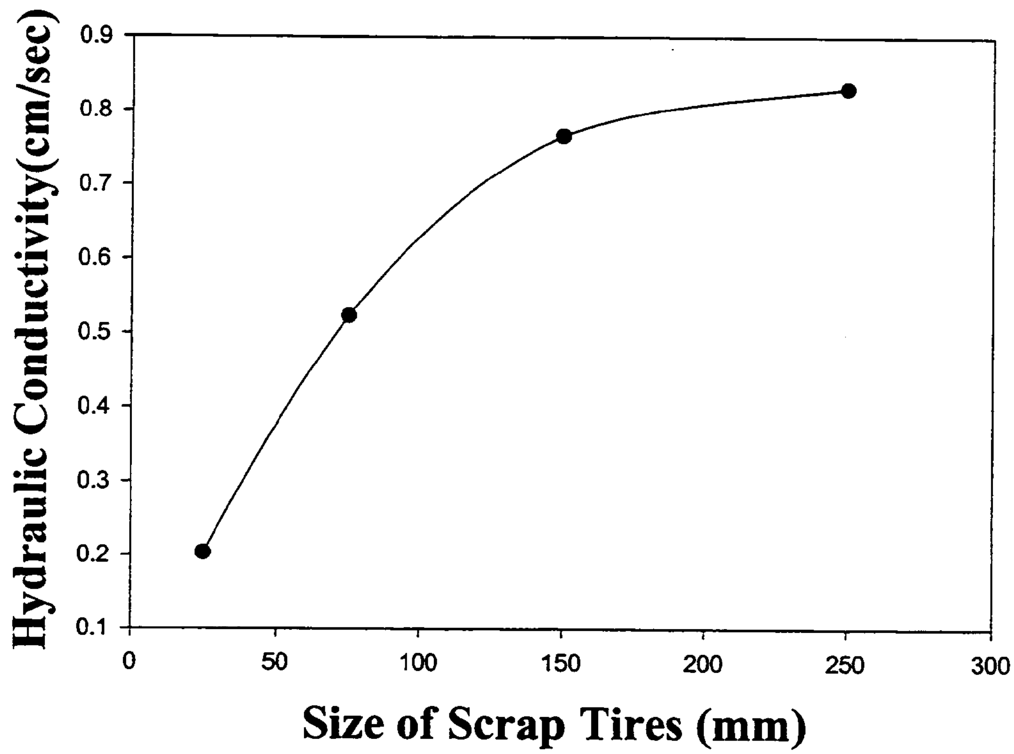


Figure 5.12 Hydraulic Conductivity and Tire Size Relationship.

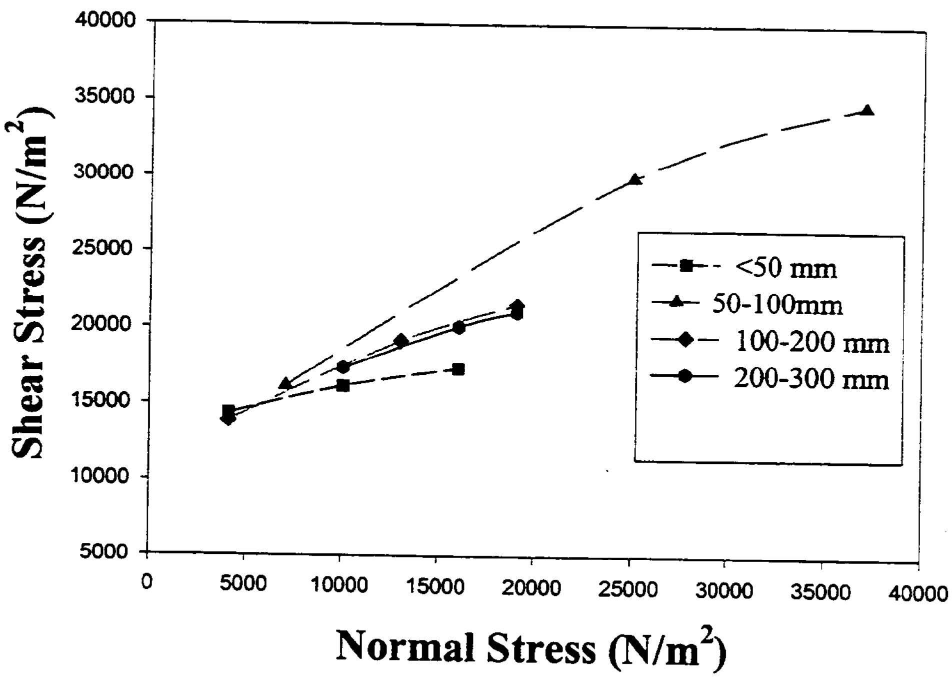


Figure 5.13 Mohr Coulomb Failure Envelop for Scrap Tires.

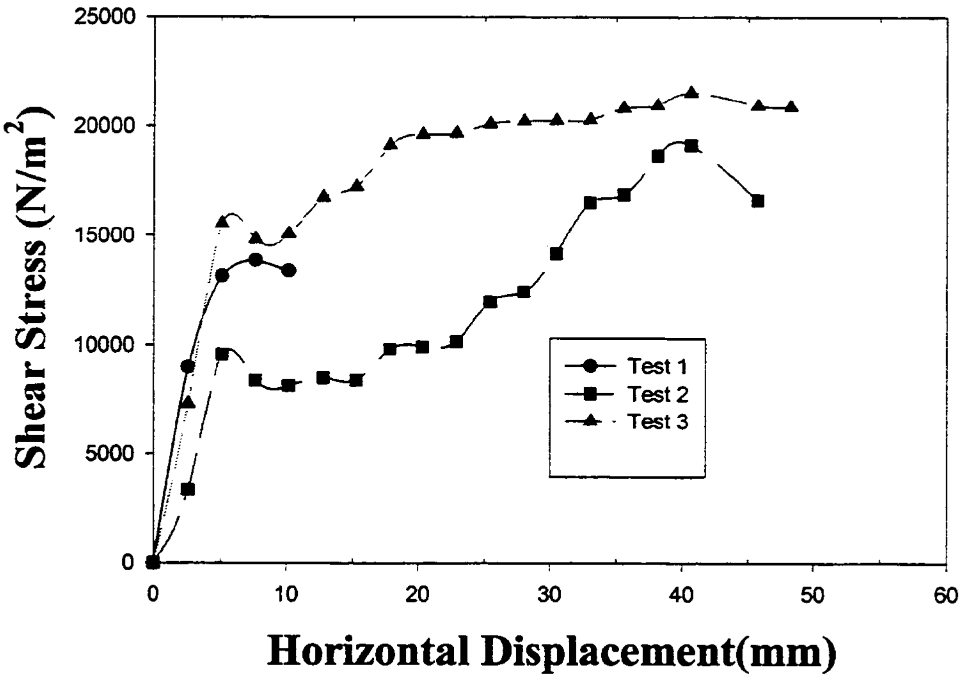


Figure 5.14 Typical Horizontal Displacement Results for 100-200-mm Tire Shreds.

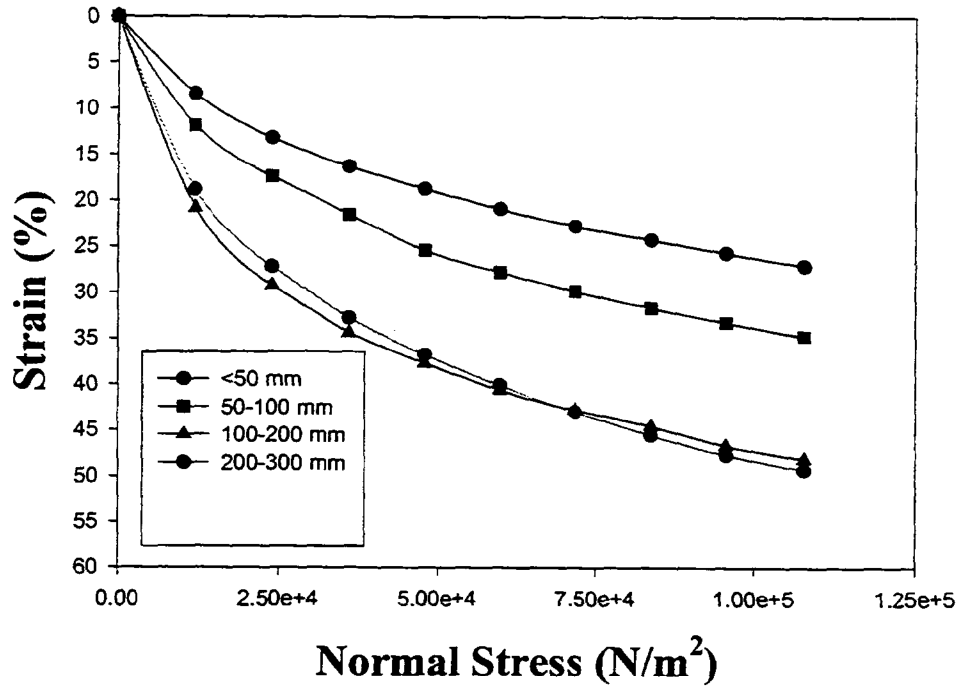


Figure 5.15 Compressibility Test Results of Scrap Tires at Various Size Ranges.

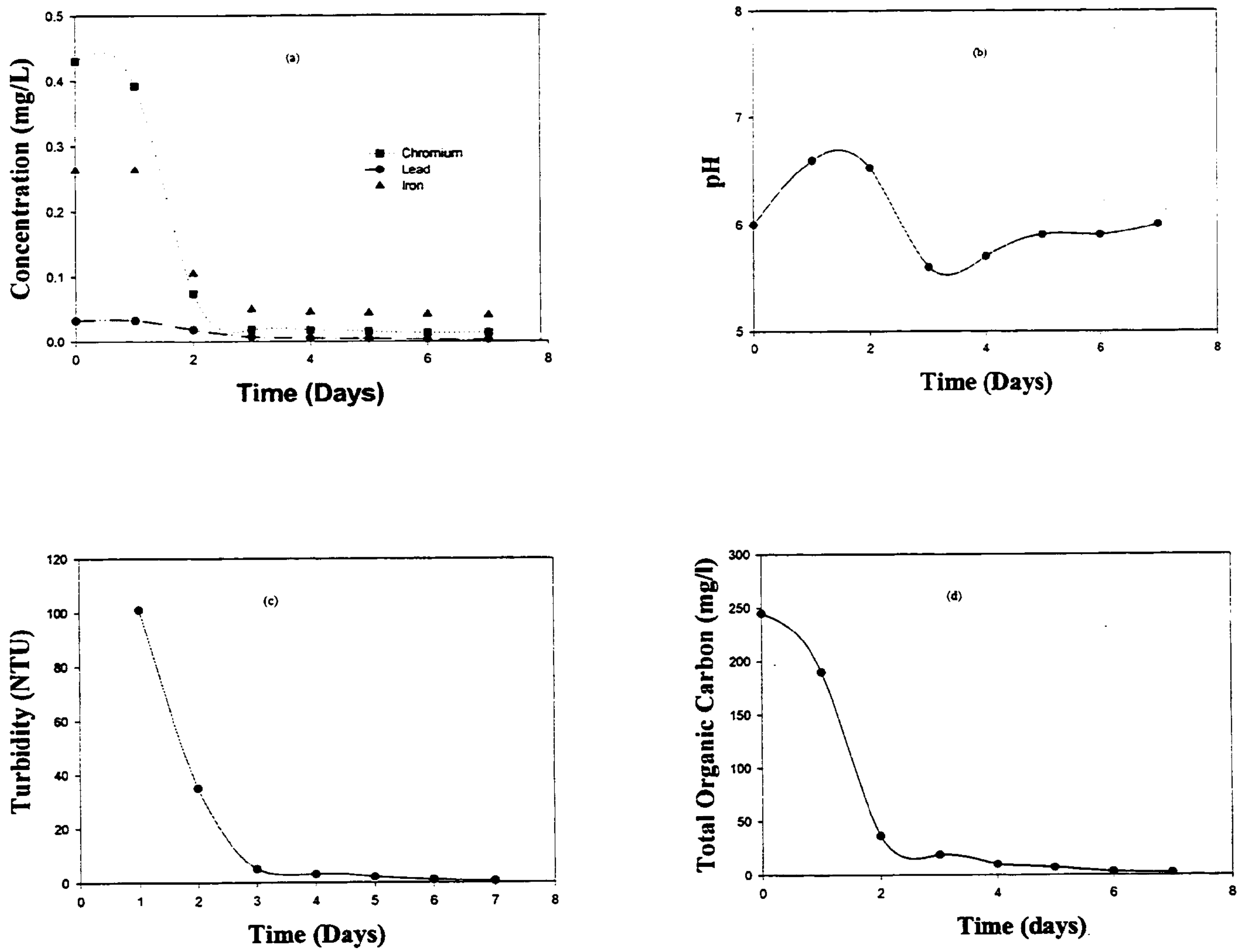


Figure 5.16 Continuous Flow Experiment Results

a Iron, Lead, and Chromium Effluent Concentrations,

b pH,

c Turbidity, and

d TOC Profiles.

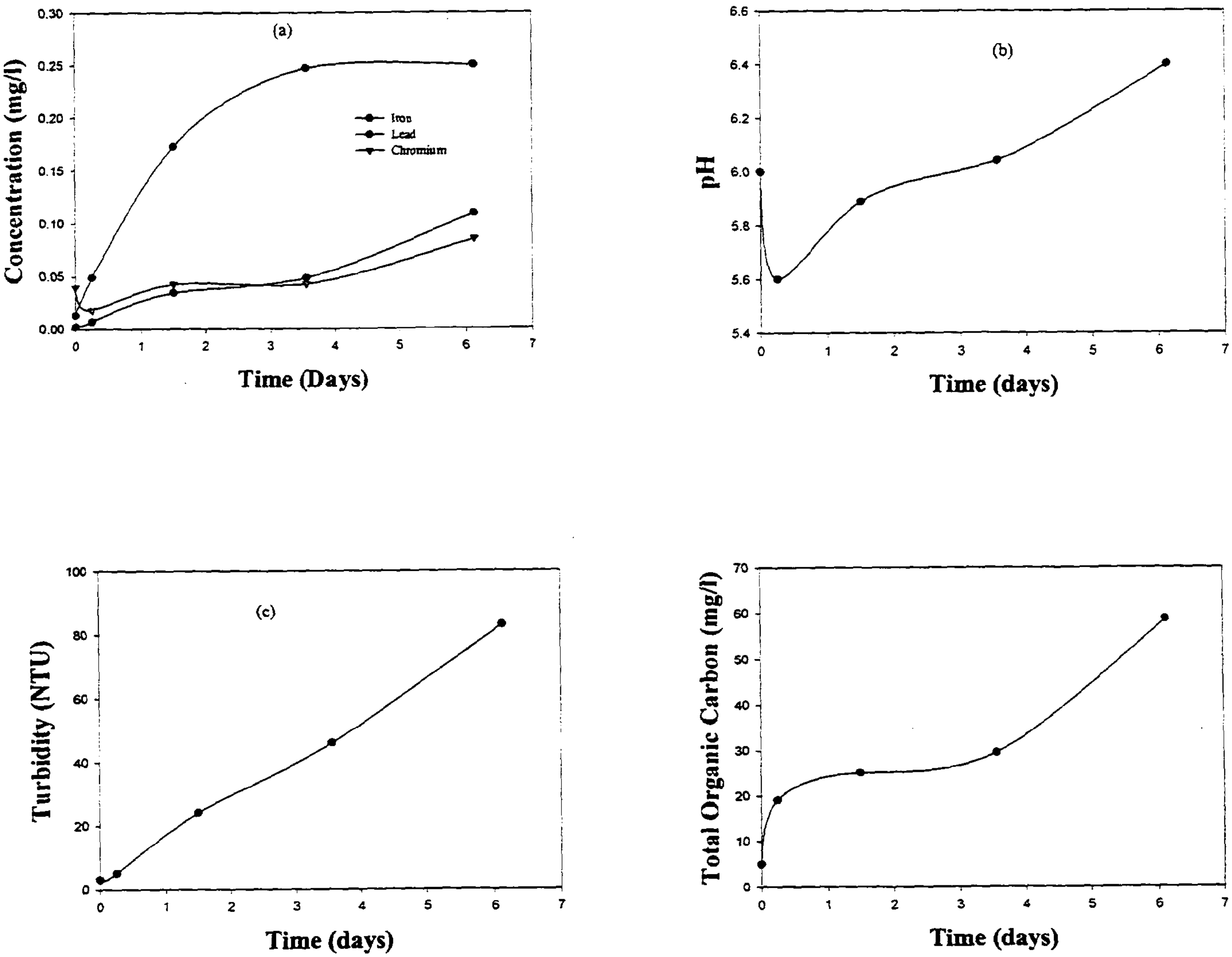


Figure 5.17 Pause Flow Experiment Results
a Iron, Lead, and Chromium Effluent Concentrations,
b pH,
c Turbidity, and
d TOC Profiles.

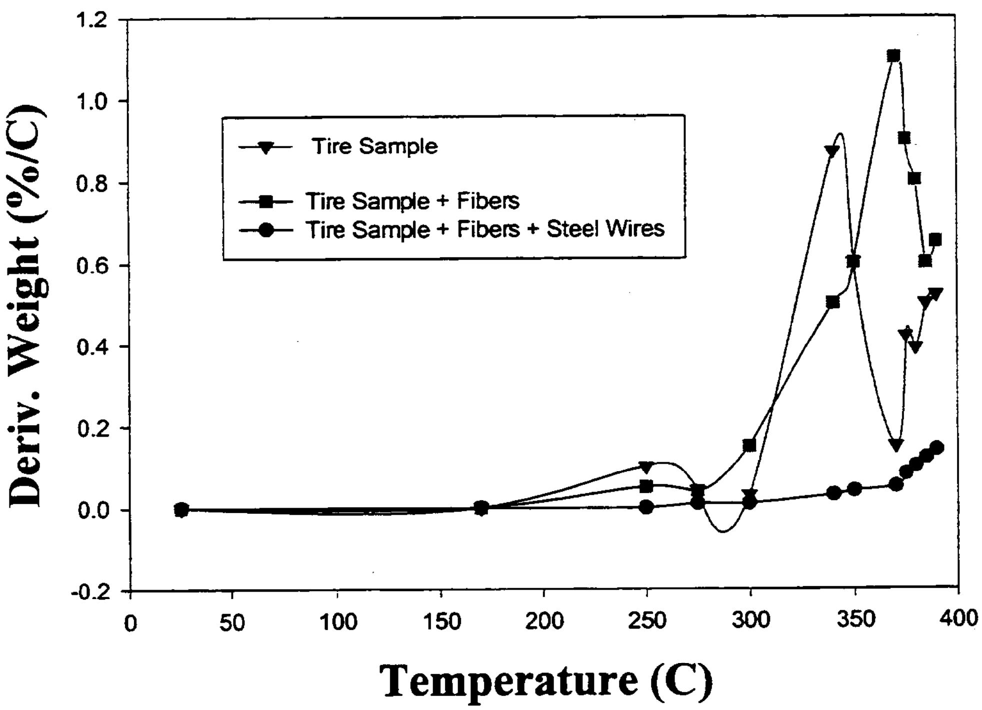


Figure 5.18 TGA Derivative Weight Curves.

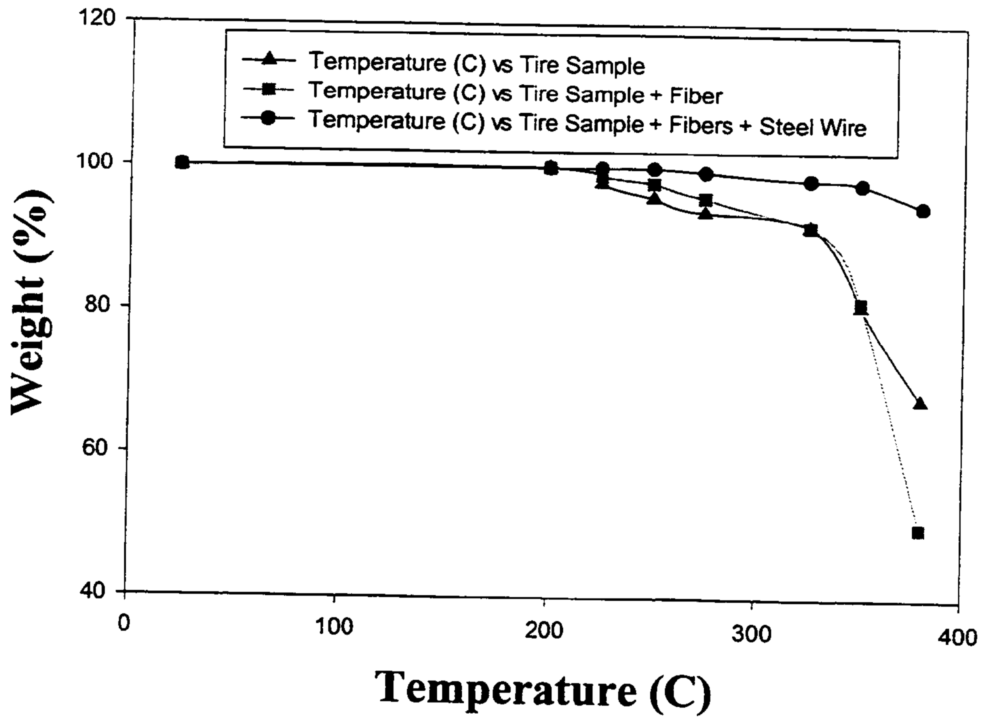


Figure 5.19 TGA Weight Curves With End Point Weight Loss.

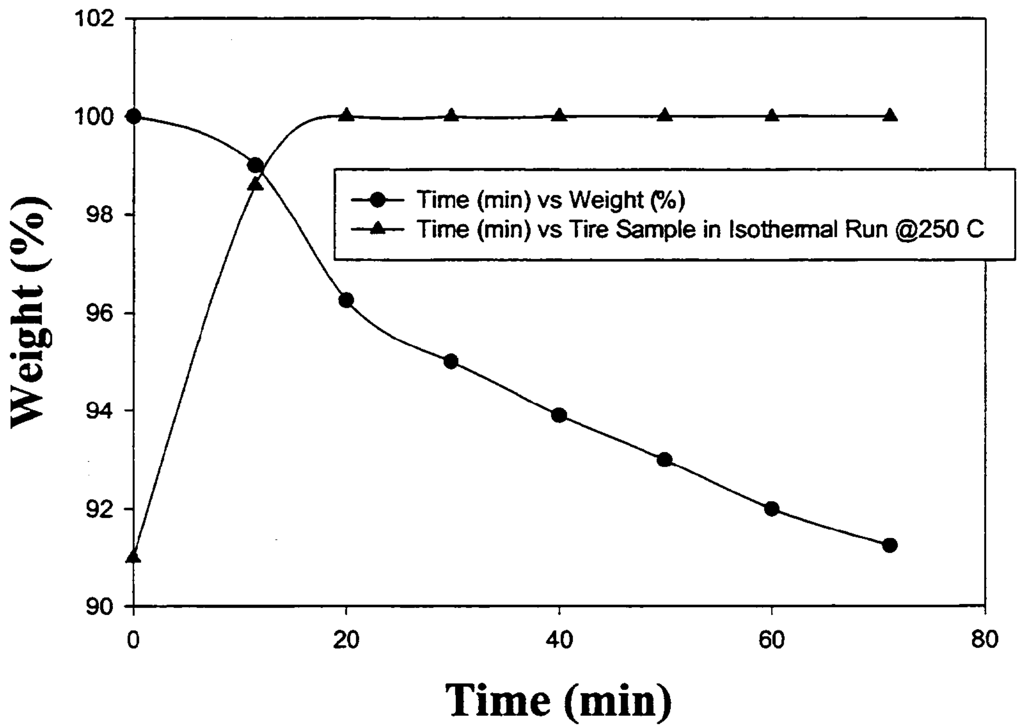


Figure 5.20 Isothermal TGA Curve for Tires Without Fibers or Steel.

6. SAMPLE SPECIFICATION

6.1 SAMPLE USE GUIDELINES

Attached is a new provisional special provision for the use of scrap tires in embankments. Approval is based upon the American Society for Testing and Materials Specification D-6270 on "Standard Practice for Use of Scrap Tires in Civil Engineering Applications." Until additional experience is gained statewide, this product will retain a provisional status.

Scrap tires are discarded automobile and truck tires that can be managed as whole, slits, shreds, chips, ground rubber, or crumb rubber. In embankment construction, tire shreds are to be utilized. Tire shreds have a basic (rectangular) geometrical shape, and are generally between 50-mm and 305-mm in size. The advantages of incorporating tire shreds in embankments include the lightweight, free drainage, durability, and insulation characteristics. The contract may be developed with tire shreds as alternate bid items or the district may choose to put it into the contract as the sole item for a chosen embankment application. If used as a sole item in a contract, then limit to three projects per district for monitoring purposes.

Provisional approval is granted for tire shreds based upon their lightweight, free draining, low earth pressure, good thermal insulation, and durable characteristics when used alone.

Provisional status requires that the use of tire shreds in embankments will be monitored by the district and by the engineering and information division, bureau of construction and materials.

Monitoring by the district will include advising the engineering technology and information division of where tire shreds have been incorporated into embankments, of any problems encountered during construction, and of any problems observed at the three month evaluation of performance of the scrap tire embankments. Monitoring is limited to visual inspection of embankment incorporating tire shreds and to the installation of settlement plates or platforms, slope indicator devices, or benchmarks along the slopes of the embankment and within or adjacent to the roadway. Readings should be taken using these devices and should continue every three months for three years to measure actual settlements versus predicted settlements. If at any point the district becomes concerned with the condition of the embankment, or any problem is demonstrated with tire shreds in embankments, the provisional special provision will be withdrawn immediately, or modified and reissued if the problem can be addressed.

The main configurations envisioned for construction are Class I Fill. Class I Fills are defined by ASTM D6270 as scrap tire layers less than 1-m thickness. The following drawing illustrates the design configuration that is possible using tire shreds in embankments, which meets the requirements of provisional special provision. Please note that the use of tire shreds is only guided by the attached drawing.

If there are any questions, please contact Robert C. Klotz, P.E., engineering technology and information division, bureau of construction and materials at (717) 787-287.

6.2 Sample Specification

I. DESCRIPTION – This work describes the construction of embankments utilizing scrap tires (tire shreds). Tire shreds have geometrical shapes (rectangles) and are generally between 5.0-cm (2.0 inches) and 30.5-cm (12.0 inches) in size.

II. MATERIAL

(a) **Embankment Material.** Embankment construction materials includes scrap tires as backfill, common borrow excavation, foreign borrow excavation, and selected borrow excavation.

1. General. ASTM D6270 defines Class I Fills as scrap tire layers less than 1.0-m (3.3 feet) thick. Provide tire shreds with the following physical characteristics:

1.a Gradation. Provide tire shreds that meet the following specifications (in accordance with ASTM D 6270):

Sieve Size	Percent Passing
300-mm (11.8 inches)	100 percent
200-mm (7.9 inches)	75-100 percent
38-mm (1.5 inches)	25 percent maximum.
4.75-mm (3/16 inches)	1 percent maximum.

1.b Physical Properties. Provide tire shreds meeting the physical properties as follows:

Property	Value	Procedure
Specific Gravity	1.16 ± 0.14	ASTM D 642
Minimum Dry Weight Density	400-kN/m^3	ASTM D 698
Hydraulic Conductivity	≥ 1-cm/sec	ASTM D 2434
Angle of Friction	≥ 22°	ASTM D 3080
Cohesion	≥ 4.3-kPa	ASTM D 3080
Compressibility, Initial Deformation	13+/-6 percent	ASTM D 6270
Compressibility, Final Deformation	13+/-6 percent	ASTM D 6270

1.c Deleterious Material. Provide tire shreds free of oils, gasoline, diesel fuel, hydraulic fluid, grease, wood, fibrous organic matter, ice, and snow. Provide tire shreds with less than 1 percent by weight of crumb rubber passing the No. 4 sieve (4.75-mm or 3/16 inches).

1.d Metal Belts. Provide tire shreds with less than 1 percent by weight of metal fragments, which are at least partially encased in the rubber. Provide tire shreds with metal fragments encased in rubber that do not protrude more than 25.4-mm (1 inch) from the cut edge of tire shreds on 75 percent of the pieces and no more than 50.8-mm (2 inches) on 100 percent of the pieces.

2. **Other suitable embankment materials.** Section 206.2.

3. **Separation Geotextile.** Section 735. Use Class 4 nonwoven geotextile.

III. CONSTRUCTION

(a)General. Section 201.

(b) Material Handling. Section 106.06. Do not mix tire shreds with organic matter such as fertilizer.

(c) Site Preparation. Section 206.3.

(d) Placement. Section 206.3. Once embankment base has been prepared, place the class 4 geotextile separation layer between tire shreds and the compacted mineral soil. Provide sufficient length to completely wrap around scrap tires. Do not place tires below the seasonal high water table.

e) Compaction. Section 206.3(b)1.

IV. MEASUREMENTS AND PAYMENT

(a) Scrap Tires. Cubic Meters (Cubic Yards).
(b) Other Suitable Embankment Materials. Section 206.4. Cubic Meters (Cubic Yard).
(c) Geotextiles. Section 735.

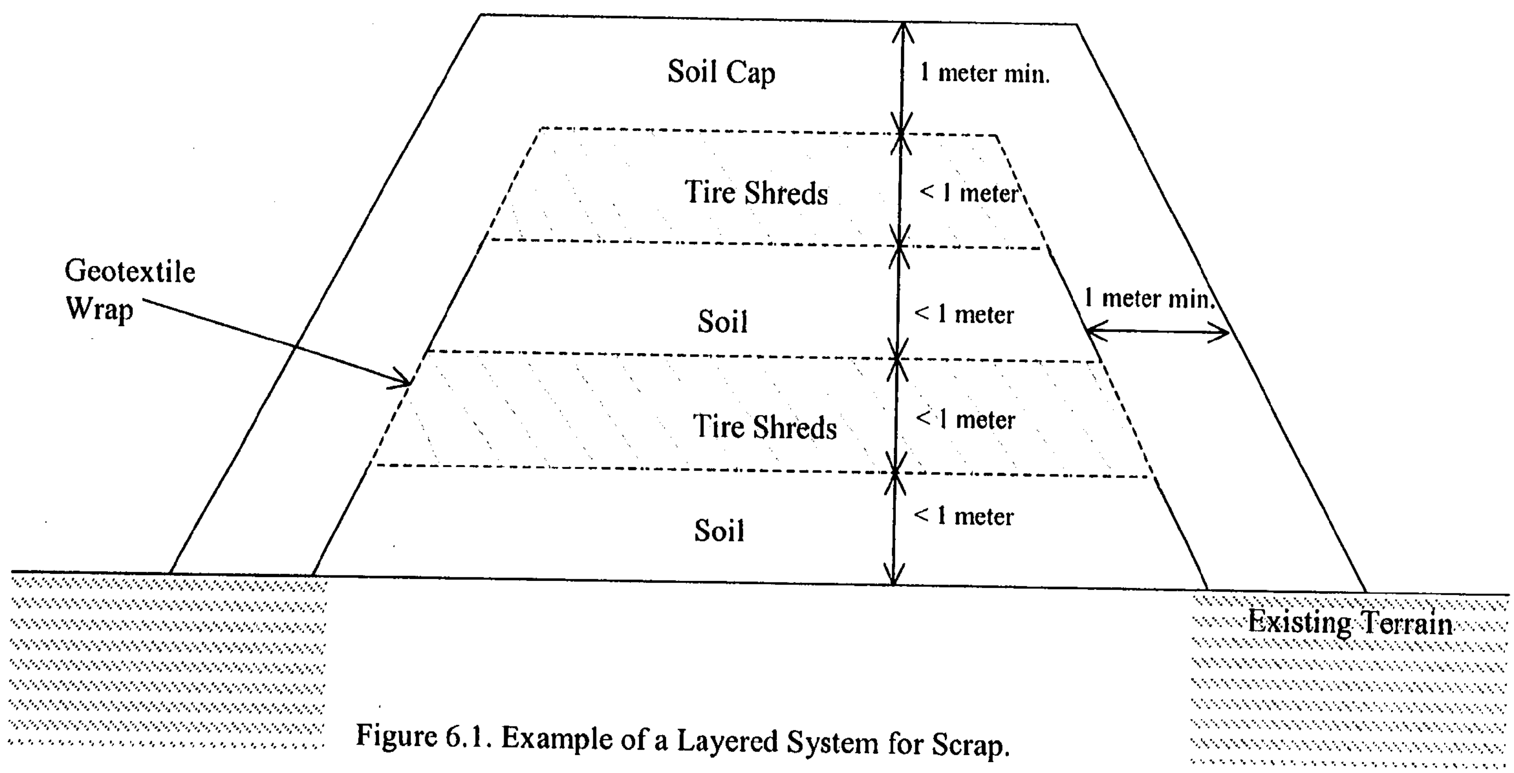


Figure 6.1. Example of a Layered System for Scrap.

7. CONCLUSIONS AND RECOMMENDATIONS

Scrap tires are discarded automobile and truck tires that can be managed as whole, slits, shreds, chips, ground rubber, or crumb rubber. In embankment construction, tire shreds are to be utilized. Tire shreds have a basic (rectangular) geometrical shape, and are generally between 50 mm and 305 mm in size. The advantages of incorporating tire shreds in embankments include the lightweight, free drainage, durability, and insulation characteristics.

Thirteen states have utilized scrap tires in embankments. Over 90 projects in these states have been conducted using scrap tires in civil and environmental engineering applications. Previous research indicates that problems with exothermic reactions have occurred in Washington and Colorado due to the very large thickness of the scrap tire fills. It is postulated that these tire fills caught on fire as a result of the oxidation of the steel belts in combination with an increase in temperature, which may have created a spark of the steel belts. This document provides guidance to reduce the risk of exothermic reaction. The following design guidelines should be followed to avoid exothermic reactions:

1. Tire shreds should be utilized in construction of embankment fills.
2. The gradation of scrap tires should have a maximum of 1 percent by weight passing the No. 4 sieve.
3. The scrap tires should be free of oils, gasoline, diesel fuel, hydraulic fluid, grease, wood, fibrous organic matter, ice, and snow.
4. Tire shreds should have less than 1 percent by weight of metal fragments, which are at least partially encased in the rubber. Tire shreds should also have metal fragments encased in rubber that do not protrude more than 25.4-mm (1 inch) from the cut edge of tire shreds on 75 percent of the pieces and no more than 50.8-mm (2 inches) on 100 percent of the pieces.

Another important aspect in the design of embankments utilizing tire shreds is the location of the water table. In this study, column tests were conducted to simulate field conditions where tire shreds may be placed above or below the water table. Laboratory test results show that placement of tire shreds above the water table will have little to no environmental impact on its surroundings. However, the placement of tire shreds below the water table was shown to have a negative impact on the environment. Thus, it is recommended that tire shred embankments be built above the water table. If a tire shred embankment is to be built below the water table, precaution in the design and construction of the embankment must be taken to assure that water does not pond up in the embankment.

Slope stability in the design of an embankment is a primary engineering concern. PENNDOT utilizes PASTABLM to conduct slope stability analysis using limit equilibrium procedures. In designing embankments utilizing tire shreds, it is recommended that a layered system be utilized where tire shreds and conventional soils are placed in alternating layers. Moreover, to be on the conservative side, it is recommended that the tire layer should not be greater than 1 meter in thickness. This will also aid in reducing the potential for exothermic reactions. In conducting slope stability analysis of a layered system the critical shear strength parameters are utilized to determine the failure surface.

Laboratory testing was conducted to determine how the chemical and physical properties change as tire shred size increases. Physical properties such as specific gravity and water adsorption showed no change as the size of tire shreds increases. Gradation of tire shreds were also tested and the results were comparable to other researchers. The hydraulic conductivity showed an increase as tire shreds size increased. Laboratory compaction test were conducted on tire shreds and showed that increasing the compaction energy had little effect on the final compaction density. In the field, standard compaction equipment such as smooth wheeled rollers or vibratory rollers can be utilized to compact tire shreds. Large-scale direct shear and compression tests were also tested for tire shreds using a 4-ft^2 direct shear box. Direct shear results showed an increase in shear strength as the particle size of tire shreds increases. Also, as the density of the tire shreds increased, the shear strength increased. Compression tests showed that as the scrap tire size increased, compressibility increased.

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APPENDIX A

PROVISIONS FOR SCRAP TIRE USE IN OTHER STATES

A1. COLORADO

EVISION OF SECTION 203

EMBANKMENT CONSTRUCTION

Section 203 of the Standard Specifications is hereby revised for this project as follows:

Subsection 203.10 shall include the following:

The planned surcharge settlement time requirement from the completion of the surcharge construction to the beginning date for surcharge removal is estimated to be no more than 180 calendar days. The actual time requirement will vary according to the actual settlement curves generated at the project site. The Contractor shall coordinate time requirements with the project Engineer at no cost to the project.

The CDOH Research Branch below the proposed shredded tire embankment will place Four-inclinometers. After the embankment areas has been cleared and leveled, the Contractor shall cover the leveled area with an initial one-foot thick lift of embankment material. The contractor shall not excavate into the landfill subsurface during installation of the inclinometers.

Following placement of the initial one foot of embankment material, the Contractor shall stake and excavate two trenches at I-76 station 352+00 and 354+50 in the surface of the initial embankment material. The trench lengths shall be as shown on the plans and shall be 8 to 12 inches deep and at least 6 inches wide. CDOH Research Branch Personnel will install the inclinometer pipes.

The Contractor shall complete the above two trenches ten (10)-calendar days prior to beginning the actual embankment construction within this area. The Contractor shall not resume embankment construction before the research branch has finished the installation and taken initial readings.

Following placement of inclinometers in the trenches the Contractor shall backfill the trenches with Structure Backfill described in Section 206 as revised.

The Contractor shall excavate two more trenches at the same stations 7 feet above the existing ground level after embankment is placed. These trenches shall be 6 to 8 inches, deep and at least 6 inches wide.

REVISION OF SECTION 203
EMBANKMENT CONSTRUCTION

The Contract or shall not resume construction until inclinometer installation by the CDOH Research Branch is complete. Any inclinometer instrumentation above or below the ground surface damaged by vandals or construction forces shall be replaced at the Contractor's expense.

Subsection 203.18 shall include the following:

Trenching, backfilling, and Structure Backfill (Special) for inclinometer installation will not be measured and paid for separately but shall be included in the work.

REVISION OF SECTION 203

SHREDDED TIRE FILL (COMPLETE IN PLACE)

Section 203 of the Standard Specification is hereby revised for this project as follows:

Subsection 203.06 shall include the following:

(c) Shredded Tire Fill shall consist of chipped or shredded tire pieces supplied by the Division at the Waste Management Incorporated Office in Lowery Landfill site. The Lowry Landfill is located at 3500 South Gun Road in Aurora, Arapahoe County.

All metal *fragments in* the shredded tire fill material shall be firmly attached and 98% embedded in the shredded tire pieces in which they are found. If metal particles or other material the Engineers determines to be unsuitable are found in shredded tire fill, the Contractor shall move this material and dispose of it at the Lowery landfill site at no cost to the Division.

Subsection 203.12 shall include the following:

Shredded tire fill shall be deposited in layers 2 feet or less in thickness before compaction. Each layer of shredded tire fill shall be compacted and kneaded into place by three passes of with a landfill type sheetsfoot roller or a D8 or equivalent type dozen.

Subsection 203.18 shall include the following:

Pay Item	Pay Unit
Place Shredded Tire Fill (Complete In Place)	Cu.Yds.

Payment for Place Shredded Tire Fill (Complete In Place) shall be full *compensation for* all work and materials required to complete the item including haul, placement, compaction, and removal and disposal of unsuitable material.

SHREDDED TIRE FILL

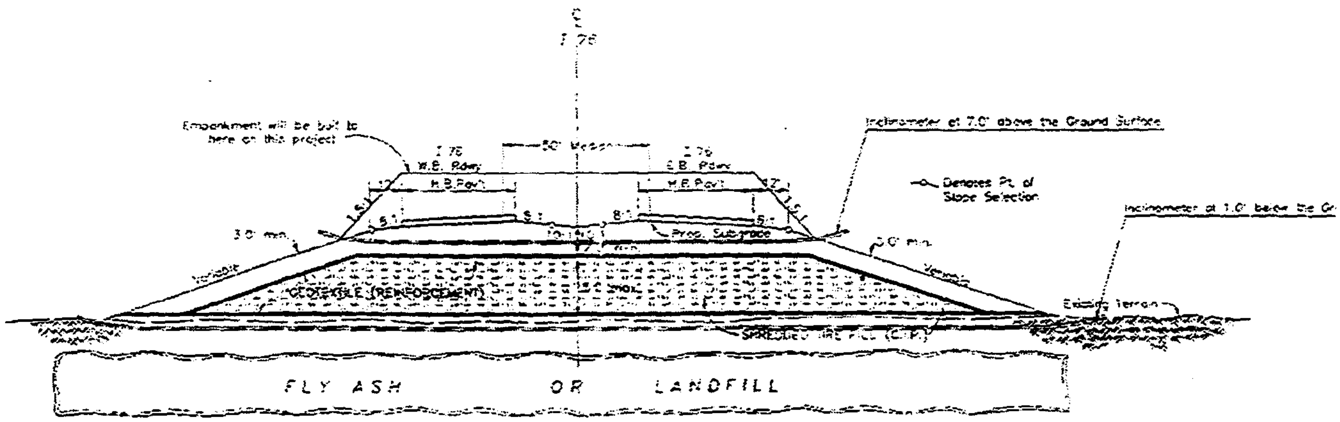


Figure A1 Shredded Tire Fill

A2. North Carolina

1-2511 BB | Rowan County North Carolina | 8.1631502

CHIPPED WASTE TIRES IN EMBANKMENTS:

1.1 DESCRIPTION

The work covered by this section consists of placing 8,180 cubic yards of chipped waste tires within the embankment to be constructed from Y-4 Rev. Station 120+53.299 to Y-4 Rev. Station 130+19.943.

The Engineer reserves the right to delete all or any portion of this item of work and the provisions of Articles 104-6 and 109-6 of the Standard Specification shall not be applicable to this work.

2.1 MATERIAL

The material shall be chipped waste tires. Ninety-nine percent (99%) of the chipped waste tires shall be three (3) inches or less in size, measured in any direction, and shall be relatively wire free. Relatively wire free shall mean that ninety percent (90%) of the chipped waste tires shall not have exposed wire extending more than 1/4" beyond the surface of the tire rubber. The contractor to the extent deemed practical by the Engineer shall minimize the presence of loose wires. The tire chips shall be free of any contaminates such as oil, grease, etc. that could leach into the ground water. The material that accumulates around shredding machinery and associated conveyor belts (fine steel cord wire, soil, etc.) should not be mixed with the shreds. All tire material shall be processed from scrap tires taken from within North Carolina.

The Contractor shall be responsible for securing all necessary permits, which may be required for the transport and storage of chipped tire material, from the North Carolina Department of Environment, Health and Natural Resources, Solid Waste Management Section.

3.1 CONSTRUCTION METHODS

The chipped tires are to be placed in the core of the embankment section described in Section 1. 1 above. Chipped tires shall not be placed within four (4) feet of the outside limits of embankments, or sub grade, or below the elevation noted on the cross sections. See cross sections for the areas designated for chipped tire placement and typical sections for the "Chipped Tire Material Detail."

Embankments shall be constructed by placing alternate layers of mixed and blended chipped tires and embankment soil with layers of pure embankment soil. The mixing and blending shall be sufficient to minimize voids. Depth of non-compacted layers shall be as directed by the Engineer, but not more than 1 foot. The blended layer shall consist of between thirty percent (30%) and sixty percent (60%) by volume of chipped tires. An average of forty percent (40%) shall be a goal

The compaction shall be to the satisfaction of the Engineer. As a minimum, mixed and blended tire lifts shall be compacted by making four to five passes over the entire surface with a bulldozer with a minimum contact pressure of 7 psi and a minimum operating weight of 20,000 pounds or other equivalent compaction equipment. The earth layers are to be compacted in accordance with Article 235-4, Paragraph C, of the Standard Specifications.

4.1 METHOD OF MEASUREMENT

The quantity of chipped tires to be paid for will be the actual number of cubic yards of approved material, measured in trucks, which has been delivered and incorporated into the completed and accepted work. Each truck will be measured by the Engineer and shall bear a legible identification mark indicating its capacity. Each truck shall be loaded to at least its measured capacity at the time it arrives at the point of delivery. No reduction will be made for voids when making truck measurements.

5.1 BASIS OF PAYMENT

The quantity of chipped tire material, measured and provided in Section 4.1 above, will be paid for at the contract unit price per cubic yard for "Chipped Tire Material."

Payment for the chipped tires for embankment shall be full compensation for furnishing, placing, manipulating the soil and chipped tires to minimize voids, and compacting the material.

Payment will be made under:

Chipped Tire Material .... Cubic Yards

12/19/97

A3. Oregon

Approximately 580,000 shredded waste tires were placed and compacted with a dozer, then capped with 3 feet of soil and a pavement section consisting of aggregate base course and asphalt pavement. Lightweight Rubber Fill Specifications Sample Specification (Oregon Department of Environmental Quality - Adapted from State of Minnesota Department of Natural Resources) The lightweight fill shall consist of chipped rubber tire pieces meeting the following specifications:

1. 80 percent of the material (by weight) must pass an 8" screen.
2. At least 50 percent of the materials (by weight) must be retained on a 4" screen.
3. All pieces shall have at least one sidewall severed from the face of the tire.
4. The largest allowable piece is 1/4-circle in shape or 24" in length whichever is the lesser dimension.
5. All metal fragments shall be firmly attached and 98% embedded in the tire sections from which they were cut. NO METAL PARTICLES SHALL BE PLACED IN THE FILL WITHOUT BEING CONTAINED WITHIN A RUBBER SEGMENT. Ends of metal belts and beads are expected to be exposed only in the cut faces of some tire chips.
6. The lightweight fill material supplied shall weigh less than 600 pounds per cubic yard, truck measure.
7. Unsuitable material delivered to the project shall be rejected in truckload quantities and removed from the site at no cost to ODOT.
8. ODOT, by use of this material, does not absolve the supplier of the responsibility of proper disposal of the lightweight rubber fill material if the section should fail to perform as expected.

The Department of Ecology assisted in finding the material, which was provided at no cost.

A4. Washington

Sample Specification

Lightweight Fill - Special Provision (C4337)

Description: This work shall consist of placing lightweight fill (shredded tires), to the line and grade as staked by the Engineer.

Materials: Lightweight fill shall consist of shredded rubber from the stockpile, which is being provided at no cost to the Contractor, or if needed, as follows:

Shredded tire lightweight fill shall consist of 100% chipped rubber tire pieces weighing less than 700 pounds per cubic yard, truck measure. Ends of metal belts and beads are expected to be exposed only in the cut faces of the chips. All metal fragments will be firmly attached and 98% embedded in the tire sections from which they were cut. No metal particles will be placed in the fill without being contained within a rubber segment. All pieces will have at least one sidewall severed from the face of the tire. The largest allowable chip dimension shall be 24 inches or 1/4 of the original tire circular shape, whichever is the less dimension. At least 50 percent of the material by weight must be retained on a 4-inch screen, and 80 percent of the material by weight must pass an 8-inch screen.

Lightweight fill material shall be stockpiled at the same site as that indicated in the Special Provision SOURCE OF STOCKPILE MATERIALS. Unsuitable material delivered to the project or project stockpile shall be rejected in truckload quantities and removed from the site at no cost to the State. The State, by use or rejection of this material, does not absolve the supplier of the responsibility of proper disposal of the lightweight fill material.

Construction Requirements: The lightweight fill shall be constructed by end dumping by trucks or other method approved by the Engineer. The lightweight fill shall be placed in layers not to exceed three feet thick. Each layer shall be compacted by at least three passes of a D-8 Dozer equivalent or larger tracked vehicle weighing at least 72,000 pounds. A full coverage pass is a pass during which at least one track of the dozer passes over every portion of the lift surface being compacted, by traveling back and forth the length of the lift followed by a full coverage pass traveling back and forth the width of the lift and continuing to alternate travel direction on successive passes. prior to placement of the gravel base slope seal, the top of the lightweight fill shall be constructed with a top elevation 12 inches above the finished elevation to allow for shrinkage. The sides of the lightweight fill shall be overbuilt to provide for final trimming. The side slopes shall be smooth and compact.

The final trimming of the lightweight fill shall be accomplished by a backhoe with a bucket, with a thumb on it, or another method approved by the Engineer. After the final trimming, the lightweight fill shall be covered with construction geotextile for soil stabilization, as shown in the Plans. Lightweight fill shall not be exposed to petroleum products or open flames. The gravel base seal shall be placed over the completed lightweight fill as soon as possible. At least four weeks shall be allowed for consolidation of the lightweight fill under the gravel base and 0.45 foot depth of asphalt concrete pavement Class E, prior to final paving.

The Contractor is hereby alerted that reinforcing wire in shredded rubber typically precludes travel of rubber-tired vehicles over the lightweight fill.

Measurement:
Lightweight fill will be measured by the cubic yard of shredded rubber in place after final trimming.

Payment: The unit contract price per cubic yard for "lightweight fill in place" shall be full pay for furnishing all labor, materials, tools, and equipment necessary for hauling, placing, and compacting as specified.

Any lightweight fill material that is furnished in addition to the stockpiled source provided will be paid for under the item "Force Account - Additional Lightweight Fill Material," as provided in Section 1-09.6.

For the purpose of providing a common proposal for all bidders, the State has entered an amount for the item "Force Account- Additional Lightweight Fill Material" in the bid proposal to become a part of the total bid by the Contractor.
For information about projects described in this section, contact:

Ed Shustak, Designer
John Hart, Project Engineer
Washington DOT (Grays Harbor) (360)533-9352

A5. Indiana

EMBANKMENT CONSTRUCTED OF CHIPPED OR SHREDDED TIRES AND GRANULAR FILL

This work shall consist of using chipped/shredded tires along with approved granular fills for constructing embankment in accordance with 105.03.

MATERIALS

The materials shall be in accordance with the following.

Borrow	203
Compacted Aggregate Base, Size No. 53	303
Geotextile	**913.18**

Type III or type IV chipped tires meeting the requirements of 329 IAC 2-9-3 and as follows will be delivered to the project site by the tire chip source, which has been selected at no cost to the Contractor or to the Department. The LaPorte District Construction Engineer may be contacted for additional information concerning the source and stockpiles of tire chips.

(a). The tire chips will be substantially free of loose metal fragments. Exposed metal along the cut faces of the tire chips will not be considered loose metal fragments. However, attached residual metal protrusions (beads and belts) extending beyond the cut faces of tires will be kept to a minimum.

(b). The tire chips supplied will be reasonably clean and free from contaminates such as oil, grease, etc., that could affect the quality of ground water.

(c). Tire remains from fires will not be used.

Granular fill shall be in accordance with 903.04 except the top size shall not exceed 10 mm (3/8 in.). The Contractor shall submit a granular fill sample to the LaPorte District Materials and Tests to determine the thickness of the granular material to be placed on top of each layer of tire chips. The layer thickness will be determined fourteen calendar days after submission of the sample.

Cohesive encasement material shall be clay loam, silty clay loam, sandy clay, silty clay, or clay in accordance with 903.02.

CONSTRUCTION REQUIREMENTS

Tire chips may be stored within the R/W of the project with the approval of the Engineer. The Contractor will be required to secure these stockpiles to reduce the likelihood of fire. They shall not be placed adjacent to commercial or residential areas. Stockpiling shall be considered a temporary measure to assist in construction activities and material contained therein shall be incorporated into the fill within 14 calendar days of the inception of the stockpile. The stockpiled volume shall not exceed 2000 cubic meters (2600 cubic yards).

The subgrade shall be prepared in accordance with Section 201 and a 150 mm (6 in.) thick layer of compacted aggregate base shall be placed and compacted in accordance with 203. A layer of geotextile shall be laid on the compacted aggregate base as shown on the plans. The geotextile shall be laid transversely with an overlap between rolls of 450 mm (18 in.). End to end splices in the geotextile will not be permitted. The transverse splices of the geotextile shall be pinned with hog ring clips.

A 300 mm (1 ft) thick lift of tire chips shall be placed on the filter fabric. A layer of granular fill of the thickness specified by the Materials and Test office shall then be placed and worked with a disk or similar device to achieve penetration of the granular fill into the voids in the layer of tire chips. The tire-fill mix shall result in a substantially uniform distribution of materials so as to promote isolation of individual tire chips by separating them with granular soils. Additional quantities of the granular fill may be required to be placed and worked to achieve the desired mix. Each layer of tire chips and granular fill shall be placed full width of the roadway cross section. Compaction of the tire-granular fill mix shall be performed with a smooth vibratory compactor in accordance with 408.03(d) and weighting 10 ton. It is expected that 6 to 8 passes shall be required to achieve proper compaction. However, the number of passes may be adjusted at the time of compaction. Following compaction, an 80 mm (3 in.) layer of the granular fill material shall be placed prior to the placement of the next layer of tire chips.

The tire-fill mix shall be covered with 0.9 m (3 ft) of cohesive encasement material. The encasement material shall be placed and compacted at the same time as the tire chip lift is placed. Seeding of the encasement material shall be in accordance with 621.

Special on-site and laboratory testing will be conducted by the Department and Purdue University. The Contractor shall allow access and time for the installation and monitoring of instrumentation by the Department.

The Contractor shall install settlement plates as shown on the plans.

If an agreement between the approved tire chip source and the Department is not executed, or if suitable shredded tire supplies can not be identified, obtained, or an adequate supply maintained pursuant to such agreement, the Contractor shall substitute borrow for tire chips and granular fills, as directed

If the procedure fails to provide a suitable embankment and if directed, the Contractor shall remove the tire-fill mix and the geotextile from the embankment. The disposal of the excavated mix will be as directed by the Engineer. The embankment shall then be reconstructed using borrow in accordance with 203.

METHOD OF MEASUREMENT:

Granular fill will be measured by the cubic meter (cubic yard) placed. Tire chips will be measured by the cubic meter (cubic yard), complete in place by final cross sections and the average end area method minus the final quantities of the granular material and the compacted aggregate base placed. The cross sections will be taken prior to the placement of the encasement material. Compacted aggregate base will be measured in accordance with 303.15. Geotextile will be measured in accordance with 616.11. Settlement plates will be measured in accordance with 204.04. Encasement material will be measured by the cubic meter (cubic yard) based on the theoretical volume to the neat lines as shown on the plans. If required, borrow will be measured in accordance with 203.27.

BASIS OF PAYMENT:

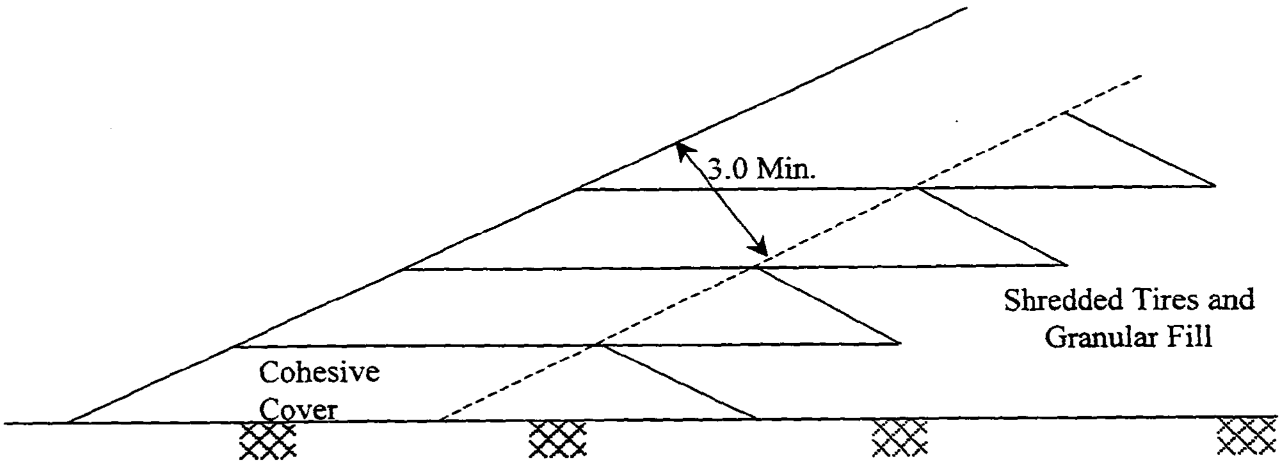
The accepted quantity of granular fill and the tire chips will be paid for at the contract unit price per cubic meter (cubic yard.). Compacted aggregate base will be paid for in accordance with 303.16. Geotextile will be paid for in accordance with 616.12. Settlement plates will be paid for in accordance with 202.05. Borrow will be paid for in accordance with 203.28. The accepted quantities of encasement material will be paid for at the contract unit price per cubic meter (cubic yard), complete in place.

If the Contractor is directed to obtain and place borrow material in lieu of the tire-granular fill mix, the borrow will be paid for in accordance with 203.28.

Payment will be made under:

Pay Item	**Pay Unit Symbol**
Encasement Material	m3 (CYS)
Granular Fill	m3 (CYS)
Tire Chips	m3 (CYS)

The pay item of tire chips shall be for the work required by the Contractor to incorporate the chips into the work. The chips will be stockpiled on the project site at no cost to the Contractor.



Scale: NOT TO SCALE

Figure A2 Toe of Slope Showing Placement of Three-Foot Minimum Cohesive Encasement

A6. New York

ITEM 17203.0398 M TIRE SHRED EMBANKMENT

DESCRIPTION:

Provide, place, and compact tire shreds to the lines and grades shown on the plans or as directed by the Engineer. Prior to beginning work, provide the Engineer with copies of all necessary permits required to store and transport tire-shreds, as issued by the New York State Department of Environmental Conservation.

MATERIALS:

Provide tire shreds that:

a. are free from contaminants such as oil, gasoline, diesel fuel, grease, hydraulic fluid, wood or other fibrous organic matter, ice and snow, and remnants of tires that have been subjected to fire.

b. have at least one sidewall severed from each tire shred.

C. have no metal fragments protruding more than 50 mm from the cut edge of any tire shred, and no more than 25 mm on 75% of the shreds.

d. have less than 1% by weight of metal fragments, which are not at least partially encased within a tire shred.

e. have less than 10% by weight of individual tire shreds with a maximum dimension greater than 300 nim.

f. meet the following gradation requirements:

Sieve Size	Percent Passing By Weight
300 mm	100
200 mm	75 - 100
38 mm	0 - 25
4.75 mm.	0 - 1

Tire shred material approval is based upon visual inspection and/or sieve analyses performed by the Regional Geotechnical Engineer or his representative.

09/30/98

ITEM 17203.0398 M - TIRE SHRED EMBANKMENT

CONSTRUCTION DETAILS:

Place tire shreds such that:

a. the maximum loose - lift thickness does not exceed 300 nun.

b. the tire shred lifts are spread in uniform thickness over the full width of the section.

C. a uniform gradation of tire shreds is maintained throughout the embankment.

d. the tire shreds do not become contaminated during the work by oil, gasoline, diesel fuel, grease, hydraulic fluid, wood or other fibrous organic matter, or ice and snow.

Compact each tire shred lift with a minimum of eight passes of a vibratory or non-vibratory smooth steel wheel roller with a minimum nominal gross weight of nine metric tons. Operate the roller at a maximum speed of 2 m/s during compaction.

METHOD OF MEASUREMENT:

Measurement for payment is the number of metric tons of tire shreds, as determined from certified truck scales, incorporated into the work conforming to the requirements of this specification and in accordance with the lines, grades, and typical section(s) shown on the plans or as directed by the Engineer.

BASIS OF PAYMENT:

The unit price bid includes the cost all of labor, materials and equipment necessary to properly complete the work.

9/30/98

A7. Minnesota

PROJECT DESCRIPTION:

The subject project involves repairing an embankment failure and completing construction of the NW ramp. Foundations help was requested on the afternoon of Jan. 16, 1992 and the required plans arrived in our office on Feb. 20, 1992. On March 5, 1992 enough snow had cleared to allow a field inspection and selection of boring locations. The solution commenced with undisturbed borings and lab testing.

IN-SITU SOILS DESCRIPTION:

Four borings, were taken by the Mn/DOT Foundations crews to supplement the district borings. The fieldwork was completed on March 24, 1992. Progress was slowed by two weeks of rain and an equipment failure. The borings, indicate a layer of plastic silty loam trapped under 25 feet of embankment fill. The silt content exceeds 80% in this layer and the moisture content was 73%. Direct shear tests indicate a friction angle of 15-17 degrees and cohesion intercept of 140 psf. However, porewater pressures during construction make even these values optimistic. The silt exhibits very slow draining capability.

Ground water was at a consistent elevation of 940 in the borings. This phreatic surface elevation will be important in solution phase.

GEOTECHNICAL ANALYSIS:

The failure is of the deep-seated rotational type with no lateral translation evident. Excess pore water pressure in the silt layer from embankment construction cannot escape fast enough and was the likely failure source. The swamp bottom slopes slightly to the west.
S.P. 5880-146
June 4, 1992

The existing and proposed cross section at station 328+00 was selected for the stability model. A network of 21 stability runs exceeding 2,400 failures was then checked. Due to the deep-seated nature of the failures a berm or flattened slope (4:1 minimum possible) will not adequately stabilize the embankment within the right of way.

A lightweight fill design consisting of shredded tires is recommended to keep the embankment loading in the failed area at or below the existing load. The existing roadway at the failure section is eight feet (eleven feet with the surcharge) from completion. Continued construction with normal weight fill would guarantee additional failures. The often suggested idea of removing the unstable soil in the failure area would require an estimated 33 feet of excavation. Potential problems also exist in the weight of hammer soil trapped below the backfill near station 334+00. To make the majority of the ramp consistent one solution was designed for all the problem areas. A lightweight ramp design will be the safest (F.S. = 1.3), quickest and most cost effective solution available. This office has attained oral permission from Joseph Otte of the MPCA on June 1, 1992 to use shredded tire chips in this design above the ground water.

The Contract Administrator and Contractor are advised that Mr. Otte (ph. 612-296-8411) may be of great help locating shredded tire chip sources. He informed me a 1,000,000-tire stockpile is located about 15 miles from the project. Also, Monte Neimi of First State Tire (ph. 612-434-0578) should be contacted about possible royalties for his tire chip patent. In the past he has requested $ 0.05 per cubic yard of shredded tire chips used.

SPECIFICATIONS AND RECOMMENDATIONS:

Based upon our exploration and analysis of the project we offer the following sequence of recommendations and explanations:

1. Remove the existing embankment to elevation 941 from station 327 to 335 and provide transition tapers to stations 326 and 336. This should be about 1-foot above the ground water surface. All remaining swamp excavation and work below elevation 941 shall remain as originally planned.

2. Place one layer of Type 5 Geotextile Fabric, Spec. 3733 with the roll direction perpendicular to centerline and sew all adjacent pieces. Quality control shall be in accordance with Spec. 3733.3 and the Schedule of Materials Control. Normal fabric construction practices shall be used, e.g. no equipment is allowed on the fabric until one foot of material is placed, keep the fabric out of ultraviolet light before placement.

3. Install settlement plates at stations 328+00 and 334+50, about 8 feet left of

   centerline on top of the fabric. The plate elevations and approximate fill fabric. The plate elevations and approximate fill surface elevations should be recorded a minimum of once a week during construction.

4. Place the shredded tire chips at the location indicated on the attached cross sections in one-foot lifts. The chips should meet the following specifications:

   Ninety percent of the material (by weight) must pass an 8" screen. Eight inches shall be the maximum desired dimension.
   A minimum of 50% of the material (by weight) must be retained on a 4" screen.
   All pieces shall have at least one of the sidewalls removed.
   All metal shall be 95% embedded in the tire pieces. No free metal fragments shall be allowed in the fill.

The shredded tires shall weigh less than 600pounds per cubic yard', loose volume.
A representative sample shall be submitted the Project Engineer for approval before delivery.

For cost estimates, tire chips on county projects have been supplied and delivered from the metro area to Lake County for $ 3.25 per cubic yard, $ 0.50 per cubic yard for shorter hauls and free to local jobs. If a sufficient number of tires are available, one supplier said 4,000 cubic yards could be chipped per day. An estimated quantity of 30,200 cubic yards (loose volume with 20% compaction expected) of shredded tires will be required.

Compaction shall be done with a dozer moving in a zigzag pattern. We expect three passes will be required to achieve ordinary compaction but field modification may be required. The initial lift shall be 2 feet thick to protect the geotextile, then subsequent lifts shall be 1 foot. Side slopes shall be 3H:1V. Due to the seven month loading from the original embankment without significant settlement no waiting period will be required between lifts. Settlement during construction of the underlying soils should be nonexistent in the preloaded areas due to a final net decrease in overburden pressure. The top of the tire chip fill shall be 5 feet below the finished profile. Some elastic compression of the chips is expected when the granular borrow is placed. Up to thirty-five percent has been measured on a DNR project. We expect a minimum of 1-foot compression in the deepest sections, giving a deadweight of 6± feet over the chips to reduce deflections.

5. Cover the top and sides of the shredded tire chips with one layer of Type 5 Geotextile Fabric, Spec.3733 in the same manner as required in recommendation no. 3. This will encapsulate the chips, add two layers of reinforcing strength, and slow the migration of subgrade fines into the tire chip voids. An estimated 22,900 square yards will be required for this encapsulation.

6. Place a second set of settlement plates on the upper geotextile next to the first set described in recommendation no. 3. Cut a small hole in the geotextile to extend the first set of plates through the upper fabric. Continue reading both sets of settlement plates as construction continues.

7. Place a minimum of 1-foot of Granular Borrow, Spec. 3149.2A, on the fabric as a working base for continued embankment construction at the toe of the tire chip slopes. The slopes may be filled out with any common borrow approved by the Project Engineer. Complete the subgrade with Granular Borrow, Spec. 3149.2A.

8. After consultation with Duane Young in the Pavement Design Unit the following flexible pavement design options are offered:

Full Depth:	1.5" Type 41 Wearing Course Mixture
	1.5" Type 31 Binder Course Mixture

4.5" Type 31 Base Course Mixture

Agg. Base: 1.5" Type 41 Wearing Course Mixture
2.0" Type 31 Base Course Mixture
6.0" Class 6 Aggregate Base

The district should select the option they feel is most appropriate. An R-value of 50 and 20-year design lane of 500,000 EASL's was used for the preceding recommendation.

Foundations Investigation and Recommendations

The chips should meet the following requirements:

1. An eight-inch maximum dimension is desired. However, the department will allow exceptions at the Project Engineers discretion provided the questionable pieces will lay flat in the embankment. We recommend a field load test be used to settle any differences. The field test shall consist of placing a 50-psf weight on the oversize chip and observing deformation. If the Mn/DOT representative determines substantial flattening has occurred it shall be deemed acceptable. A standard weight 8" nominal concrete block (40 pounds and 15.5" x 7.5" x 7.75") would be the ideal size for the test. A rigid board and sandbag may also work.

2. A minimum of 50% of the material (by weight) must be retained on a 4" screen. This requirement may be visually inspected. The intent is to limit the amount of crumbs and fines.

3. All pieces shall have at least one of the sidewalls removed.

4. All metal shall be 95% embedded in the tire pieces. No free metal fragments shall be allowed in the fill.

5. The shredded tires shall weigh less than 600 pounds per cubic yard, loose volume.

A 8. Rubber Manufacturers Association

Design Guidelines to Minimize Internal Heating of Tire Shred Fills

Background

Since 1988 more than 70 tire shred fills with a thickness less than 1 m and an additional ten fills less than 4 m thick have been constructed. In 1995 three tire shred fills with a thickness greater than 8 m experienced a catastrophic internal heating reaction. These unfavorable experiences have curtailed the use of all tire shred fills on highway projects.

Possible causes of the reaction are oxidation of the exposed steel belts and oxidation of the rubber. Microbes may have played a role in both reactions. Although details of the reaction are under study, the following factors are thought to create conditions favorable for oxidation of exposed steel and/or rubber: free access to air; free access to water; retention of heat caused by the high insulating value of tire shreds in combination with a large fill thickness; large amounts of exposed steel belts; smaller tire shred sizes and excessive amounts of granulated rubber particles; and the presence of inorganic and organic nutrients that would enhance microbial action.

The design guidelines given in the following sections were developed to minimize the possibility for heating of tire shred fills by minimizing the conditions favorable for this reaction. As more is learned about the causes of the reaction, it may be possible to ease some of the guidelines. In developing these guidelines, the insulating effect caused by increasing fill thickness and the favorable performance of projects with tire shred fills less than 4 m thick were considered. Thus, design guidelines are less stringent for projects with thinner tire shred layers. The guidelines are divided into two classes: Class I Fills with tire shred layers less than 1 m thick and Class II Fills with tire shred layers in the range of 1 m to 3 m thick. Although there have been no projects with less than 4 m of tire shred fill that have experienced a catastrophic heating reaction, to be conservative, tire shred layers greater than 3 m thick are not recommended. In addition to the guidelines given below, the designer must choose the maximum tire shred size, thickness of overlying soil cover, etc., to meet the requirements imposed by the engineering performance of the project. The guidelines are for use in designing tire shred monofills. Design of fills that are mixtures or alternating layers of tire shreds and mineral soil that is free from organic matter should be handled on a case-by-case basis.

General Guidelines for All Tire Shred Fills

All tires shall be shredded such that the largest shred is the lesser of one-quarter circle in shape or 0.6 m in length; and at least one sidewall shall be severed from the tire shred.

The tire shreds shall be free of all contaminants such as oil, grease, gasoline, diesel fuel, etc., that could create a fire hazard. In no case shall the tire shreds contain the remains of tires that have been subjected to a fire because the heat of a fire may liberate liquid petroleum products from the tire that could create a fire hazard when the shreds are placed in a fill.

Class I Fills

Material guidelines. The tire shreds shall have a maximum of 50% (by weight) passing the 38-mm sieve and a maximum of 5% (by weight) passing the 4.75-mm sieve.

Design guidelines. No design features are required to minimize heating of Class I Fills.

Class II Fills

Material guidelines. The tire shreds shall have a maximum of 25% (by weight) passing the 38-mm sieve and a maximum of 1% (by weight) passing the 4.75-mm sieve. The tire shreds shall be free from fragments of wood, wood chips, and other fibrous organic matter. The tire shreds shall have less than 1% (by weight) of metal fragments which are not at least partially encased in rubber. Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tire shred on 75% of the pieces and no more than 50 mm on 100% of the pieces.

Design guidelines. The tire shred fill shall be constructed in such a way that infiltration of water and air is minimized. Moreover, there shall be no direct contact between tire shreds and soil containing organic matter, such as topsoil. One possible way to accomplish this is to cover the top and sides of the fill with a 0.5-m thick layer of compacted mineral soil with a minimum of 30% fines. The mineral soil should be free from organic matter and should be separated from the tire shreds with a geotextile. The top of the mineral soil layer should be sloped so that water will drain away from the tire shred fill. Additional fill may be placed on top of the mineral soil layer as needed to meet the overall design of the project. If the project will be paved, it is recommended that the pavement extend to the shoulder of the embankment or that other measures be taken to minimize infiltration at the edge of the pavement.

Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided. This includes, but is not limited to, open graded drainage layers daylighting on the side of the fill and drainage holes in walls. Under some conditions, it may be possible to use a well-graded granular soil as a drainage layer. The thickness of the drainage layer at the point where it daylights on the side of the fill should be minimized. For tire shred fills placed against walls, it is recommended that the drainage holes in the wall be covered with well-graded granular soil. The granular soil should be separated from the tire shreds with geotextile.

General Guidelines for all Tire Shred Fills (July 1997)

All tires shall be shredded such that the largest shred is the lesser of one quarter circle in shape or 0.6 m in length; and at least one sidewall shall be severed from the tire shred

Tire shreds shall be free of contaminants such as oil, grease, gasoline, diesel fuel, etc., that could create a fire hazard

In no case shall the tire shreds contain the remains of tires that have been subjected to a fire

Class I Fills (< 1 m thick)	Class II Fills (1-3 m thick)
Maximum of 50% (by weight) passing 38-mm sieve	Maximum of 25% (by weight) passing 38-mm sieve
Maximum of 5% (by weight) passing 4.75-mm sieve	Maximum of 1% (by weight) passing 4.75-mm sieve
	Tire shreds shall be free from fragments of wood, wood chips, and other fibrous organic matter
	The tire shreds shall have less than 1% (by weight) of metal fragments that are not at least partially encased in rubber
	Metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tire shred on 75% of the pieces and no more than 50 mm on 100% of the pieces
	Infiltration of water into the tire shred fill shall be minimized
	Infiltration of air into the tire shred fill shall be minimized
	No direct contact between tire shreds and soil containing organic matter, such as topsoil
	Tire chips should be separated from the surrounding soil with a geotextile
	Use of drainage features located at the bottom of the fill that could provide free access to air should be avoided

These guidelines were prepared by the Ad Hoc Civil Engineering Committee, a partnership of government and industry dealing with reuse of scrap tires for civil engineering purposes. The committee members are:

Michael Blumenthal, Executive Director, Scrap Tire Management Council
Mark Hope, Senior Vice President, Waste Recovery, Inc.
Dana Humphrey, Ph.D., Professor of Civil Engineering, University of Maine
James Powell, Federal Highway Administration

John Serumgard, Chairman, Scrap Tire Management Council
Mary Sikora, Scrap Tire Program Director, International Tire and Rubber Association
Robert Snyder, Ph.D., President, Tire Technology, Inc.
Joseph Zelibor, Ph.D., Former Science Director, Scrap Tire Management Council & Vice President, Partners in Research, Inc.

The committee can be contacted by calling the Scrap Tire Management Council at (202)682-4880.

APPENDIX B

FIELD DATA AND PICTURES

COMPACTION FIELD TEST

Date: 05/11/2001
Place: Renaissance Recycling Wind Gap, Pennsylvania.
Tel: (610) 863-0533

MATERIAL HANDLING

On May 11, 2001 a test embankment of shredded tires was constructed at the Renaissance Recycling tire processing facility, located in Wind Gap, Pa. figure B1. It was estimated that approximately 75 shredded automobile tires would be required per cubic yard.

SITE PREPARATION AND PLACEMENT

After scraping off the surface soil, a geotextile was placed down to separate the foundation soils from the shredded tires. An area of 10-ft by 10-ft and a height of 1-ft test embankment was built with the aid of a bulldozer figure B2. Before compaction, the weight of the shredded tires, was measured, and then placed in the test embankment figure B3. The loose (placed) density was calculated to be 20-lb/ ft^3. Figures B4, and B5 show the tires in the embankment before compaction.

COMPACTION

The scrap tires were compacted with a vibratory smooth steel wheel roller with a nominal gross weight of 10-metric-tons, figure B6, and B7. Once the compacter was able to pass over a layer of shredded tires with little to no noticeable deflection or movement under the tracks of the compacter figure B8, indicating sufficient compaction achievement, compaction was assumed complete. Fifteen passes were required for this particular configuration figures B9, B10, and B11. Figure B12 shows the embankment after compaction. Surface elevation measurements were determined after compaction figure B13, and from the known mass of shredded tires the reduced volume from compaction was calculated to be 38-lb/ ft^3.

TEST PROCEDURES

1. 10-ft by 10-ft area and 1-ft high of box was prepared.
2. The measured weight of scrap tires was filled in the box
3. The volume of the scrap tires in the box was calculated.
   Loose Density of scrap tires = mass/volume = 2,806/140 = 20-lb/ ft^3
4. The scrap tires were compacted with a vibratory smooth steel wheel roller with a nominal gross weight of ten metric tons. Fifteen passes were performed.
5. The new height was determined, and the volume of the compacted scrap tires was calculated.
   Compacted density = mass/volume = 2,806 lb/74 ft^3 = 38-lb/ ft^3

Figure B1 Scrap Tire Site at Renaissance Recycling

Figure B2 Bulldozer Used in Building Embankment

Figure B3 Fill Length, Width and Depth Measurement Before Compaction

Figure B4 Scrap Tires in Embankment Before Compaction

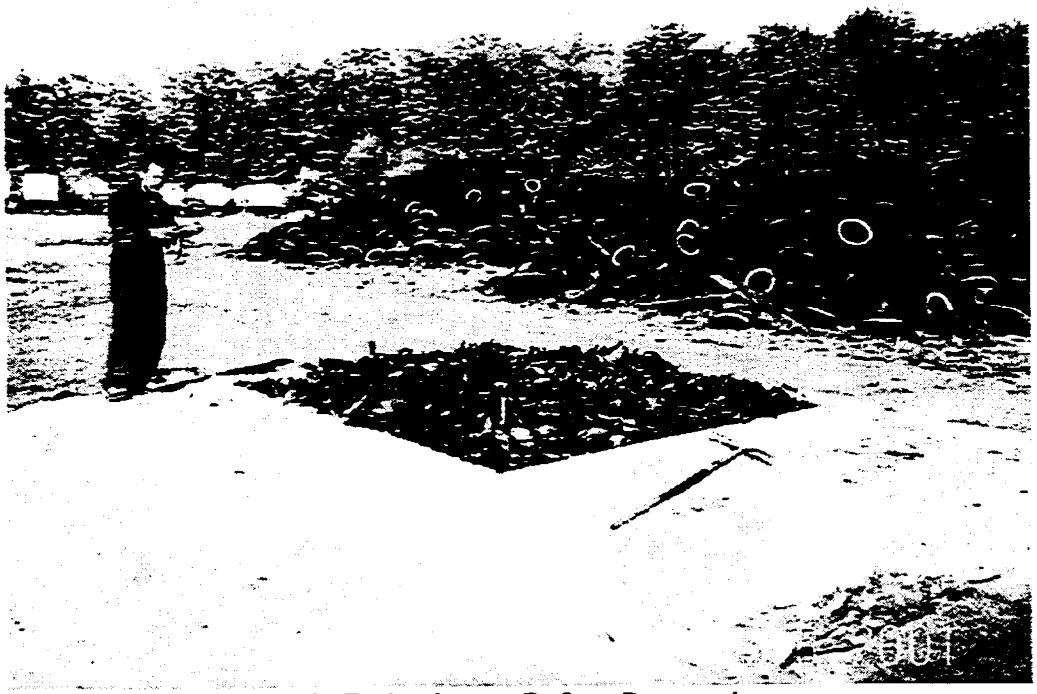


Figure B5 Scrap Tires in Embankment Before Compaction

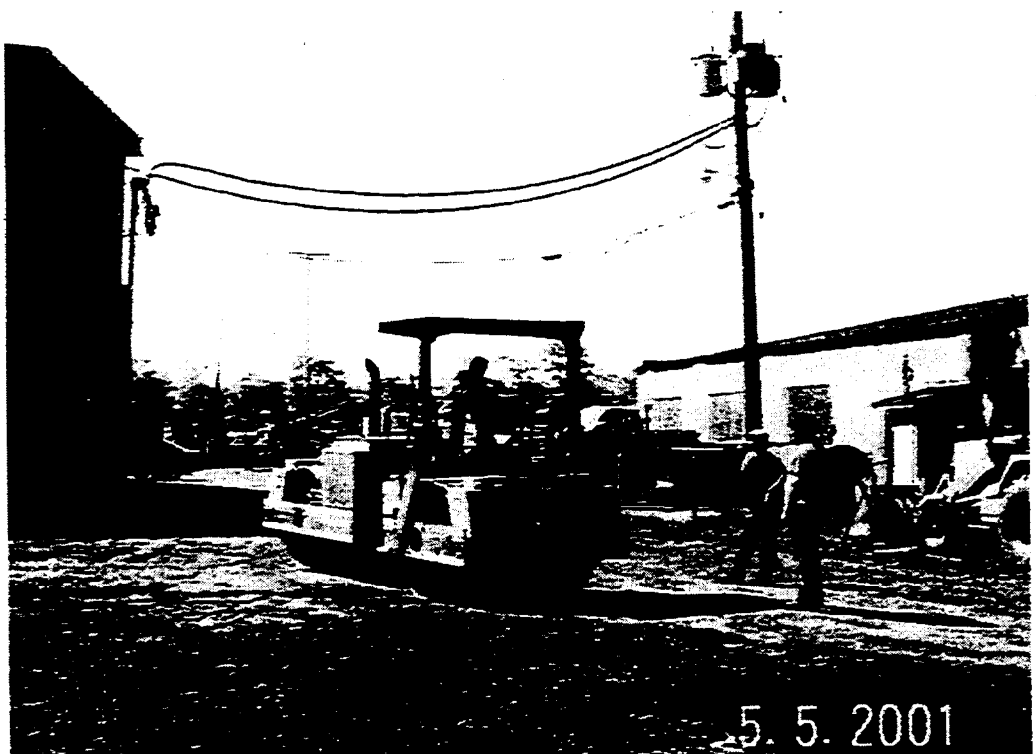


Figure B6 Vibrating Roller Used for Scrap Tire Compaction

Figure B7 Vibrating Roller Used for Scrap Tire Compaction

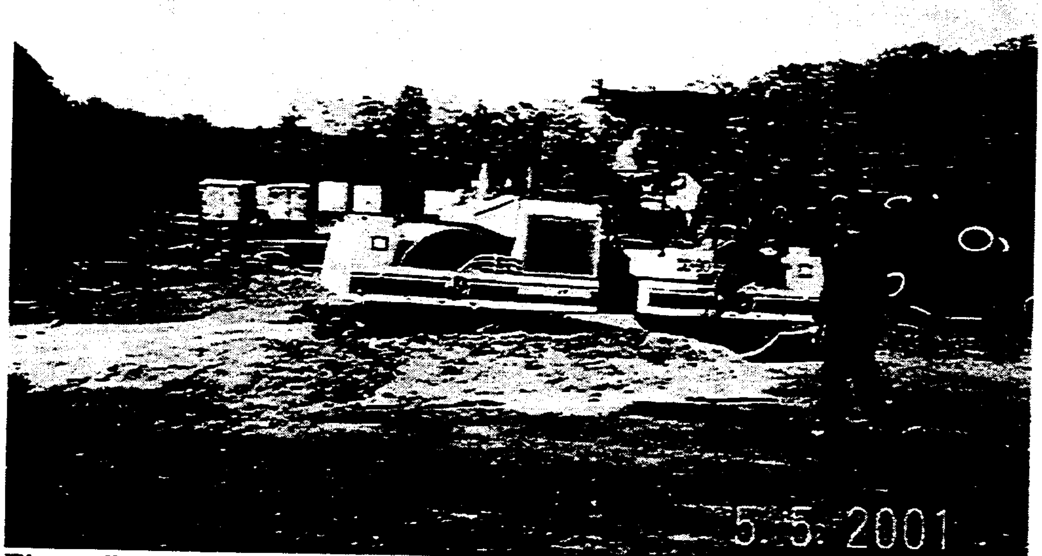


Figure B8 Tire Compression During Compaction

Figure B9 Compaction After 5-Passes

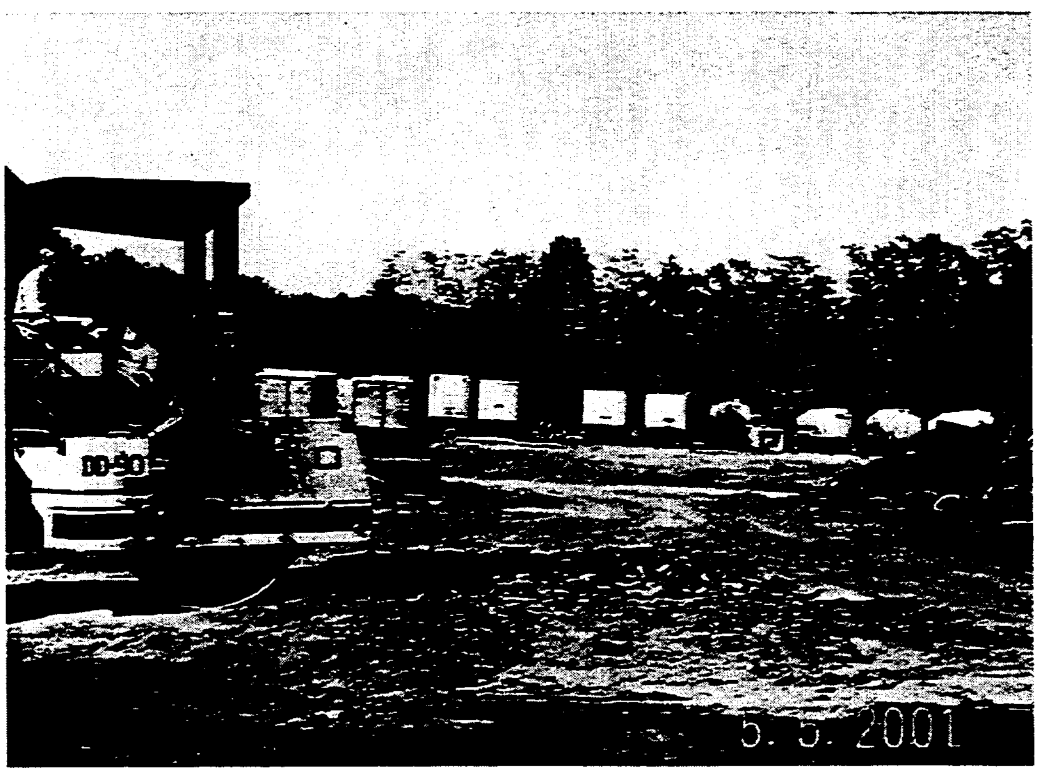


Figure B10 Compaction After 8-Passes

Figure B11 Compaction After 12-Passes

Figure B12 Scrap Tires in Embankment After Compaction

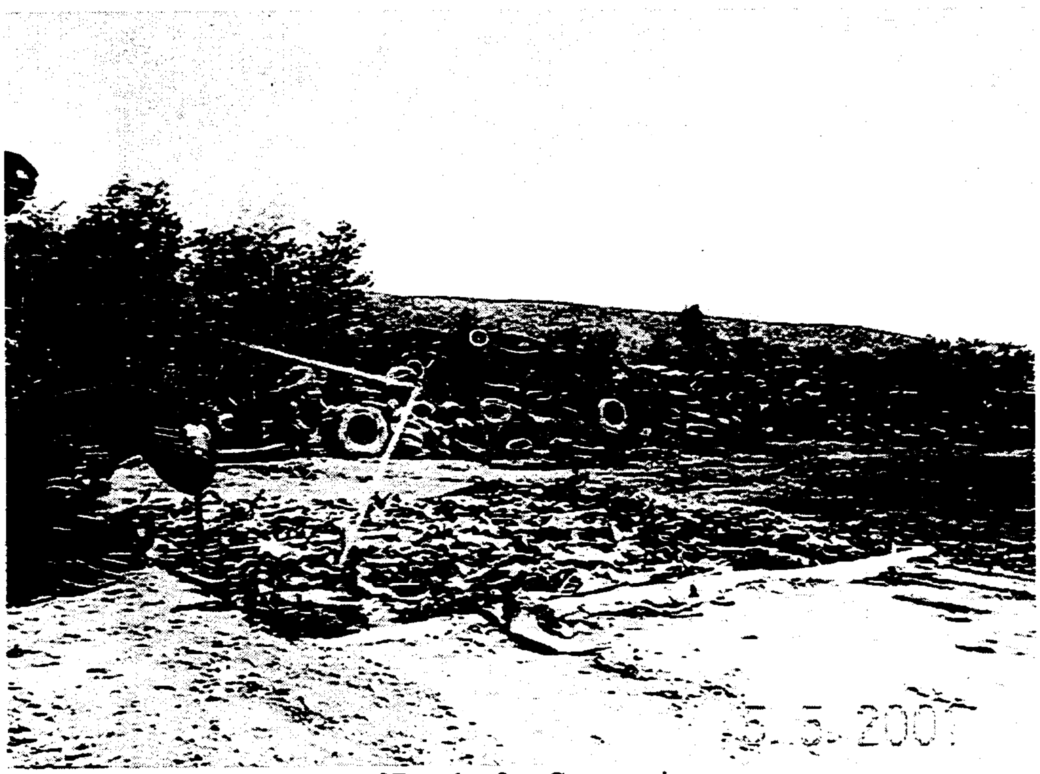


Figure B13 Measurement of Depth after Compaction

APPENDIX C

LIFE CYCLE ANALYSIS OF THE UTILIZATION OF SCRAP TIRES IN EMBANKMENTS

C1. Introduction

There are few man-made things more durable than a tire. A tire is a mixture of fabric, steel, carbon black and several different types of natural and synthetic rubber. However, all of the characteristics that make tires invaluable create a special challenge when tires become worn down. The sulfur and carbon in rubber are bonded together and inseparable, which makes tire recycling nearly impossible.

Recycling is a necessary requirement for today's world. Hundreds of millions of tires are annually discarded in the United States. The worldwide disposal rate will soon total two billion tires per year. This exponential growth of scrap tires helps supports the issue of reuse of tires. Scrap tires cannot only be reused, but they can also be converted to energy. The most common method of reuse is the conversion of scrap tires to energy. However, the conversion to energy only uses 49 percent of the total of generated scrap tires. Presently, civil engineering applications only use seven percent of the generated total of scrap tires. This number could be increased significantly if scrap tires were utilized in the construction of embankments. Scrap tires should be used as fill in the embankments instead of a traditional soil fill. This new application could have many economical advantages.

C.2 Life Cycle Cost using Value Engineering

Value engineering (VE) is an organized process with a history of improving value and quality. In simple terms, VE is a systematic approach to obtaining optimum value for every dollar spent. As practiced in VE, Life cycle costing (LCC) is an economical assessment of competing design alternatives using the concept of equivalent cost. Two methods that are used to evaluate the Life cycle costing (LCC of scrap tires in embankments:

Net present Worth Methods and the Annualized Method. The present worth method (equation 1&2) requires conversion of all present and future expenditures to a baseline of today's cost. The annualized method (equation C.1) converts initial, recurring and nonrecurring costs to an annual series of payments. As shown in tables C.1 & C.2, there are various factor tables that must be used when using the two methods. These factors are based on the number of years and the interest rate.

Recurring costs are as follows:

$$P = \frac{\left[A\left(1+i\right)^{n}-1\right]}{i\left(1+i\right)^{n}} = PWA \qquad \text{(C.1)}$$

Where:

i = interest rate per period (in decimals)

n = number of interest periods

P = present sum of money (present worth)

A = end-of-period payment or receipt in a uniform series continuing for *n* periods, entire series equivalent to P at interest rate I

PWA = present worth of an annuity factor

Nonrecurring costs (when A=$1.00) are as follows:

$$\frac{P}{F} = \frac{1}{\left(1+i\right)^{n}} = PW \qquad \text{(C.2)}$$

Where:

F = sum of money at the end of n, from the present date that is equivalent to P, with interest rate i

PW = present worth factor

N = number of interest periods

The equation, P / F, usually read as, P given F. yields the present value given the future value.

$$A = P \frac{i(1 - i)^n}{(1 + i)^n - 1} = PP \qquad \text{(C.3)}$$

Where:

A = annualized cost
P = $1.00
i = interest rate per interest period (in decimal)
n = number of interest periods
PP = period payment factor

As equation C.2, this equation could read as A given P. That is, the annualized cost given the Present cost.

Table C.1 Present Worth Method Factors (PWA)

Years	Interest rate per period, i						
	6%	7%	8%	9%	10%	12%	14%
1	0.943396	0.934579	0.925926	0.917431	0.909091	0.892857	0.877193
2	0.889996	0.873439	0.857339	0.841680	0.826446	0.797194	0.769468
3	0.839619	0.816298	0.793832	0.772183	0.751315	0.711780	0.674972
4	0.792094	0.762895	0.735030	0.708425	0.683013	0.635518	0.592080
5	0.747258	0.712986	0.680583	0.649931	0.620921	0.567427	0.519369
6	0.704961	0.666342	0.630170	0.596267	0.564474	0.506631	0.455587
7	0.665057	0.622750	0.583490	0.547034	0.513158	0.452349	0.399637
8	0.627412	0.582009	0.540269	0.501866	0.466507	0.403883	0.350559
9	0.591898	0.543934	0.500249	0.460428	0.424098	0.360610	0.307508
10	0.558395	0.508349	0.463193	0.422411	0.385543	0.321973	0.269744
20	0.311805	0.258419	0.214548	0.178431	0.148644	0.103667	0.072762
25	0.232999	0.184249	0.146018	0.115968	0.092296	0.058823	0.037790
30	0.174110	0.131367	0.099377	0.075371	0.057309	0.033378	0.019627
35	0.130105	0.093663	0.067635	0.048986	0.035584	0.018940	0.010194
40	0.097222	0.066780	0.046031	0.031838	0.022095	0.010747	0.005294

Table C.2 Annualized Worth Method Factors (PW)

Years	Interest rate per period, i						
	6%	7%	8%	9%	10%	12%	14%
1	0.943396	0.934579	0.925926	0.917431	0.909091	0.892857	0.877193
2	1.833393	1.808018	1.783265	1.759111	1.735537	1.690051	1.646661
3	2.673012	2.624316	2.577097	2.531295	2.486852	2.401831	2.321632
4	3.465106	3.387211	3.312127	3.239720	3.169865	3.037349	2.913712
5	4.212364	4.100197	3.992710	3.889651	3.790787	3.604776	3.433081
6	4.917324	4.766540	4.622880	4.485919	4.355261	4.111407	3.888668
7	5.582381	5.389289	5.206370	5.032953	4.868419	4.563757	4.288305
8	6.209794	5.971299	5.746639	5.534819	5.334926	4.967640	4.638864
9	6.801692	6.515232	6.246888	5.995247	5.759024	5.328250	4.946372
10	7.360087	7.023582	6.710081	6.417658	6.144567	5.650223	5.216116
20	11.469921	10.594014	9.818147	9.128546	8.513564	7.469444	6.623131
25	12.783356	11.653583	10.674776	9.822580	9.077040	7.843139	6.872927
30	13.764831	12.409041	11.257783	10.273654	9.426914	8.055184	7.002664
35	14.498246	12.947672	11.654568	10.566821	9.644159	8.175504	7.070045
40	15.046297	13.331709	11.924613	10.757360	9.779051	8.243777	7.105041

Referring to table C.1, the Present Worth Model calculates the present worth of a project by using the compound interest factor. The factor can be obtained by using equation C.1 or by using table C.1. Once this factor is obtained, the operational and maintenance costs are determined. Then the PW column is tallied and results in the value for the Total Present Worth Life Cycle Cost.

C.3 Discussion

During construction operation, sources of interest include transport, unloading, loading, spreading, and fill compaction. During the service life of the embankment, runoff, and leaching, can be expected.

In performing a life cycle analysis, initial construction cost must be included. These costs include loading, transportation, unloading, spreading, and fill compaction. The next cost is the annual maintenance cost. Environmental testing is included in the annual maintenance cost for tire shred fills, because of possible leaching. Testing of groundwater is to be performed when using tire shreds for fill in embankments.

Throughout the construction of an embankment the first cost to consider is the mobilization and demobilization cost. For heavy construction, the total cost is roughly estimated to be $7,075.00. The mobilization and demobilization costs include labor, and equipment. The next expenditure that must be determined is the material cost. The price of tire shreds varies from $0.40 per cubic yard to $17.00 per cubic yard. The higher end of the range usually includes transportation. Usually, the prices that don't include transportation vary from $0.40 to $1.50. The cost of purchasing and transporting the tires shreds to the project location vary from $1.50 to $17.00. When including labor, equipment, and transportation costs, less than 10 miles, for loading, unloading, and spreading, the average price for the tire shreds increases to approximately $4.66 per cubic yards. For mileage greater than 10 miles, the average cost of the placement of tire shreds can increase to $27.00 per cubic yard.

The compaction equipment, including labor, is roughly estimated at $0.22 per cubic yards. Assuming that there is insufficient material for the formation of the embankment, additional suitable material must be taken from borrow pits. The average cost for borrow excavation is about $6.23 per cubic yard, including transportation (< 10 miles), equipment and labor. The average cost for borrow excavation increases to about $30.00 per cubic yard, including transportation (>10 miles), equipment and labor.

Table C.3 Cost Summary of Material for Embankment

Material	**$ / yd^3**
Tire shreds	
Purchasing, Transportation, & Placement < 10 miles	$4.66
Purchasing, Transportation, & Placement > 10 miles	$27.00
Borrow Excavation	
Purchasing, Transportation, & Placement < 10 miles	$6.23
Purchasing, Transportation, & Placement > 10 miles	$30.00

The price of the geotextile averages to about $0.45 per square foot. The next costs are the annual expenditures. These costs include environmental testing when using a tire shred fill in an embankment.

Using tire shreds as fill in embankment construction can be more expensive than the cost for using borrow excavation. One reason for the increase is the location of the shredding plant from the construction site. Such states as California have experienced an increase of construction cost due to the locations of shredding plants. However, the cost of the different methods depends on the location of the materials relative to the location of the embankment project.

However, the cost increase is offset by the decreased cost to the government and the consumer to maintain the scrap tires in stockpiles, as shown in table C.5. The average cost to the government to maintain one stockpile is $5.50 per cubic yard. Twenty-seven states charge a fee on the sale of new tires. The fees range in price from $0.25 to $ 2.00 per tire or $5.00 per vehicle title. The states that charge fee are listed in table C.4

Most states cleaning up stockpiles are doing so with the funds collected from state fee programs. This fee could be sunset if the state would use the shred the scrap tires and use them as fill in embankments. Considering the average embankment project will utilize 1.5 million scrap tires and approximately 75 tires are used per cubic yard in the construction of an embankment, the government will save $110,000.00 per embankment project per year.

Table C.4 States with Scrap Tire Management Fees

Arkansas	Louisiana	North Carolina
Arizona	Maine	Ohio
California	Maryland	Oklahoma
Florida	Michigan	Pennsylvania
Georgia	Minnesota	Rhode Island
Illinois	Mississippi	South Carolina
Indiana	Missouri	South Dakota
Iowa	Nebraska	Tennessee
Kansas	Nevada	Utah
Kentucky	New Mexico	Virginia

LIFE CYCLE COST

Input in shaded areas. *Fill in these areas.

Project The Use of Scrap Tires in Embankments (Example)						
Location	ALT. 1					
PROJECT LIFE CYCLE (YEARS) 30	Tire Shreds					
INTEREST RATE (% in decimals) 7%						
Material	*Unit (C.Y.)	*Cost	Est.	PW		*U (C.
A) Tire Shreds	10022	4.66	46,703	46,703		
B) Conventional Fill			0			1C
C) Geotextile (sq. ft)	101200	0.45	45,540	45,540		
D)			0			
Equipment	*Unit (C.Y)	*Cost				*U (C.
A) Riding vibrating roll, 12" lifts, 5 passes	10022	0.28	2,806	2,806		
B) Riding vibrating roll, 12" lifts, 2 passes			0			1C
Total Initial Cost Impact (IC)				95,049		
Initial Cost PW Savings						
Operation/Maintenance Cost ***Escl..00%** PWA			*Est.			
A) Environmental Testing 12.409			200	2,482		
B) ________________ 12.409						
Total Operation/Maintenance (Present Worth, PW) Costs				2,482		
Total Present Worth Life Cycle Costs (TPWLCC)				**97,530**		
Life Cycle (PW) Savings						
Governments Cost for Maintaining Stockpile				**55,121**		
TPWLCC (including government cost)				**42,409**		
Total Life Cycle (PW) Savings						

Table C.5 Life Cycle Cost Example

C.4 Conclusion

Hundreds of million of tires are discarded annually in the United States. The rate of scrap tires in stockpiles is growing exponentially. To alleviate this growing problem, scrap tires must be recycled. Using scrap tires as fill in embankment is an alternative to stockpiling the tires. The following conclusions can be drawn from this study:

1. Tire shreds are economically priced. They are the cheapest material for many projects, and conserve natural aggregate resources.
2. A major cost factor of using scrap tires versus other materials for fill in embankments depends on the location of the material relative to the location of the project. However, using scrap tires as fill in embankments can clear a stockpile. The use of scrap tires, will save the government $5.50 per cubic yard cost to maintain a stockpile.
3. Utilizing scrap tires as fill in embankment construction will also aide the government to eliminate the disposal fee for scrap tires, which vary from $0.25 to $2.00. When the scrap tires are placed in an embankment the consumer will no longer have to pay this disposal fee.
4. Road embankments have the potential to use an enormous quantity of tires. The average embankment project consumes 1.5 million scrap tires.
5. Reducing the stockpiles of scrap tires not only eliminates the cost of disposal, but it will also reduce the various environmental and health hazards such as fire and disease.

APPENDIX D

TIRE SHREDDING EQUIPMENT

D.1 Overview

Whole or parts of scrap tires from automobile, truck, and off-road vehicles are shredded by utilizing equipment with knives or blades. The general design of the equipment consists of infeed/outfeed conveyors and classifiers designed to ensure a certain size of cut. Depending on the manufacturer the systems may be stationary or mobile, electric or hydraulic, off-the-shelf, or custom designed.

A typical tire shredding operation may be run in the following manner. Tires are brought into the plant and sorted. Mud, rocks, and sand are washed off the tires, which are then inspected to remove any large stones or metal objects from the treads or inside the tires. Depending on the setup, the tires may then be fed straight into a 6" primary shredder such as that shown in figure D1 followed by a 2" secondary shredder figure D2. If steel beads such as those contained in truck tires are of concern, the tires may be passed through a "DeBeader™" figure D3, where the large steel beads around the tire rim are removed (The "DeBeader™" is a rugged, simple piece of equipment which hydraulically pulls the steel head from a truck tire cleanly and efficiently). The debeaded tires are then conveyed to the shredder. From the secondary shredder the tires are then ready, and if additional shredding is required the tires can be conveyed into another shredding machine. It is at this finer stage that some of the steel (from the steel belting in most tires) is removed. Loose fabric is then vacuumed away. Figure D4 is an example of what a shredding equipment configuration might look like.

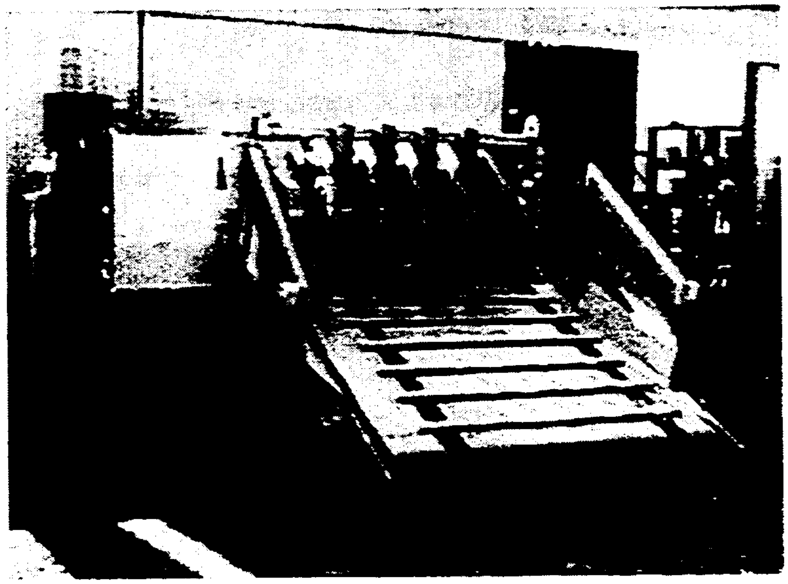


Figure D1 6" Primary Shredder

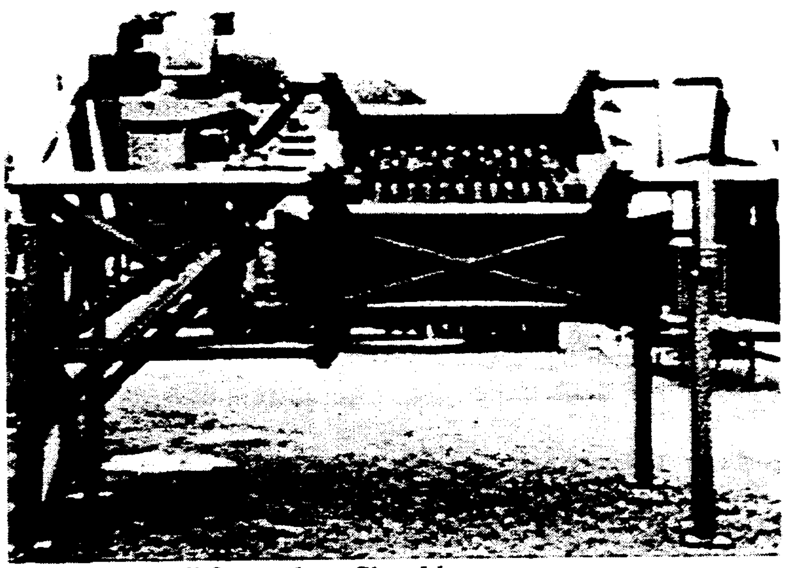


Figure D2. 2" Secondary Shredder

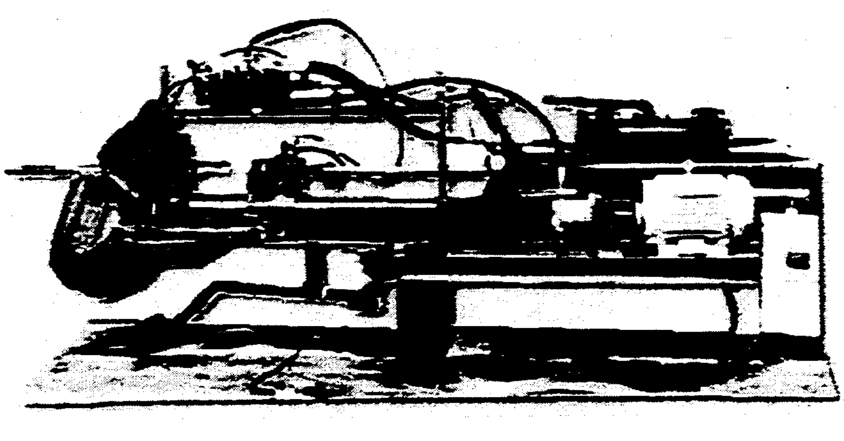


Figure D3 "DeBeader™"

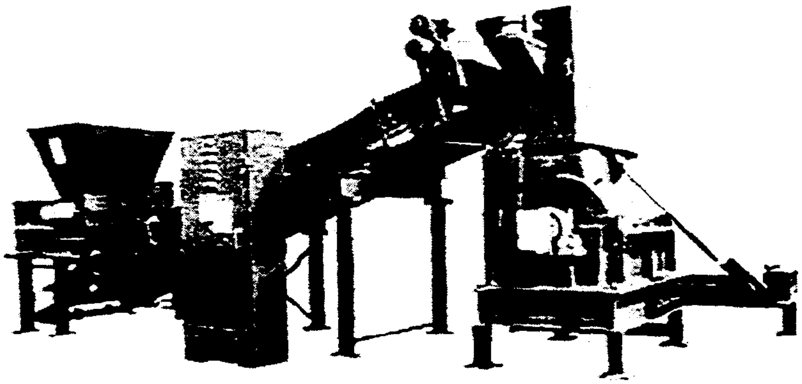


Figure D4 Typical Shredding Equipment Configuration

Capital costs for various types of shredding equipment are listed in the table D1 below. (Note: this is a representative sample of costs and output, and is not a complete list of all manufacturers)

Table D1. Scrap Tire Shredding Systems.[1]

Shredder type/manufacturer		Estimated Cost[2]	System configuration[3]	Estimated throughput[4](tons/hour)	Chip size[5]
Replaceable Cutter/	Columbus	$500-525	Portable	12 to 13	RS
	McKinnon	$435-460	Stationary	8 to 10 4 to 5	2 inches 1 inch
Triple/S Dynamics		$550-575	Portable	12 to 13	RS
		$400-425	Stationary	8 to 10 4 to 5	2 inches 1 inch
Rotary Shear/Eidal		$375-400	Portable	10 to 12	RS
		$290-315	Stationary	6 to 8 3 to 4	2 inches 1 inch
ERS		$500-525	Portable	12 to 13	RS
		$425-450	Stationary	8 to 10 3 to 4	2 inches 1 inch
Mac-Saturn		$400-425	Portable	10 to 12	RS
		$340-365	Stationary	6 to 8 3 to 4	2 inches 1 inch
Mitts & Merrill (Carthage)		$375-400	Portable	8 to 10	RS
		$250-275	Stationary	5 to 7 2-1/2 to 3	2 inches 1 inch
Shredding Systems		$450-475	Portable	10 to 12	RS
		$375-400	Stationary	6 to 8 3 to 4	2 inches 1 inch

[1]Portable systems are self-contained with diesel generator; systems include conveyors, sizing device (typically a disc screen) and magnetic for 1 inch minus chip production; 1 inch minus chip throughputs are estimates based on limited experience.
[2]Costs are estimated and will vary for each application; costs do not include recent price increases that may have occurred.
[3]"Portable" assumes 1 trailer with diesel generator; "Stationary" assumes electric power is available on-site.
[4]Estimated throughput in tons/hour.
[5]RS = Rough Shred throughput, 6 inches = one pass through cutters; 2 inches = chip size of 2 inches or less; 1 inch = chip size of 1 inch or less.