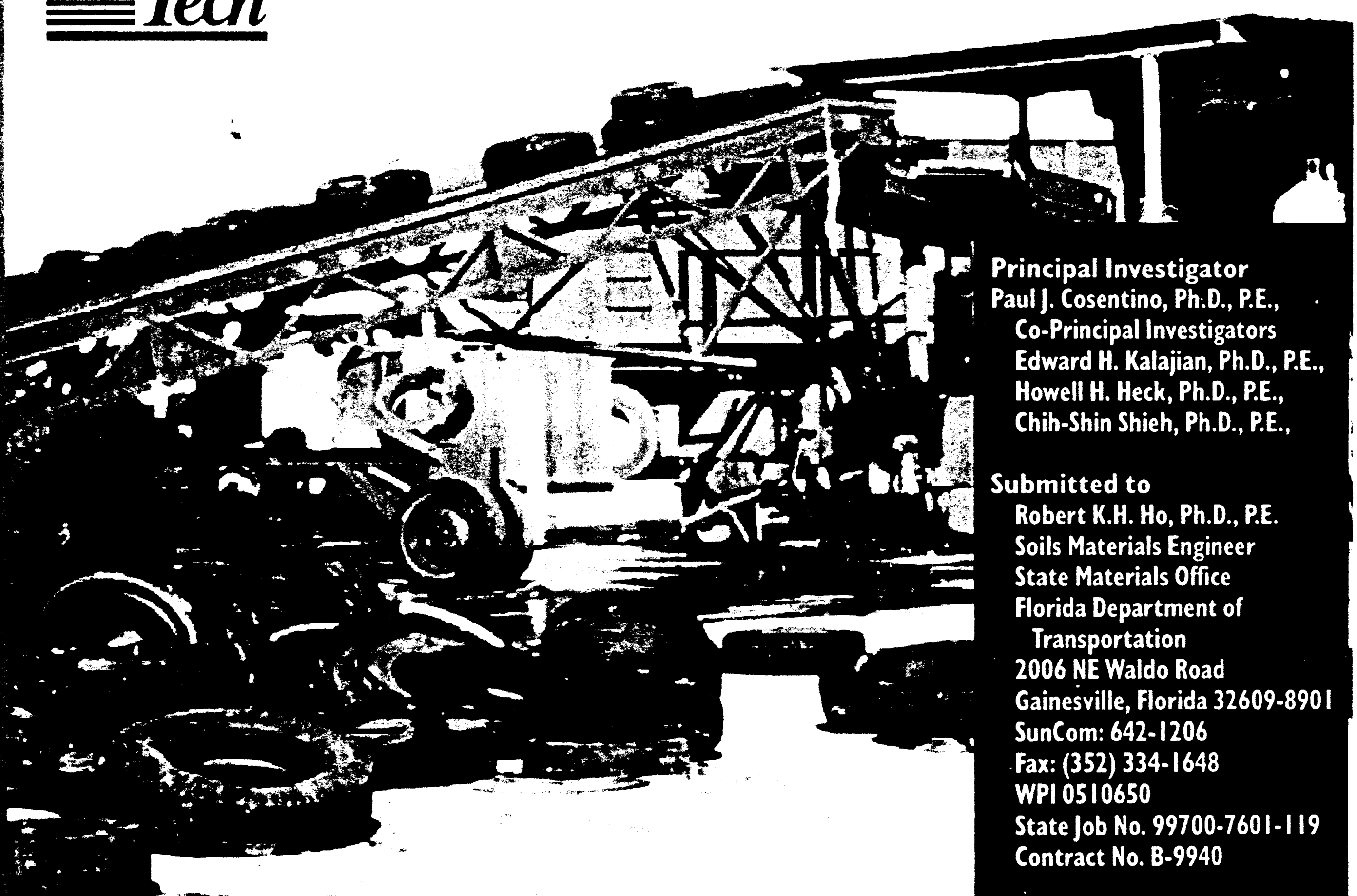
Developing Specifications for Waste Glass, Municipal Waste Combustor Ash and Waste Tires as Highway Fill Materials (Continuation)

Final Report

Volume 3–Waste Tires

Florida Tech



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WPI 0510650
State Job No. 99700-7601-119
Contract No. B-9940

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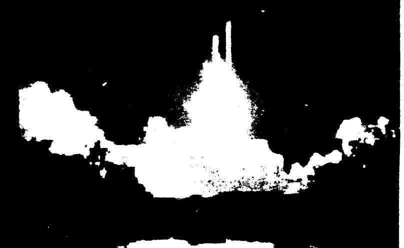

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FL/DOT/RMC/06650-7754		

4. Title and Subtitle

DEVOLOPING SPECIFICATIONS FOR WASTE GLASS, MUNICIPAL WASTE COMBUSTOR ASH AND WASTE TIRES AS HIGHWAY FILL MATERIALS (CONTINUATION)
Volume 3 of 3 (Waste Tires)

5. Report Date

APRIL 1995

6. Performing Organization Code

7. Author's

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8. Performing Organization Report No.

9. Performing Organization Name and Address

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10. Work Unit No. (TRAIS)

11. Contract or Grant No.

B-9940 WPA # 0510650

12. Sponsoring Agency Name and Address

Florida Department of Transportation
605 Suwannee Street
Tallahassee, Florida 32399-0450

13. Type of Report and Period Covered

Final Report
October 1995 to October 1997

14. Sponsoring Agency Code

99700-7601-119

15. Supplementary Notes

16. Abstract

A two year study was conducted as a continuation project for the Florida Department of Transportation (FDOT) to evaluate Municipal Waste Combustor (MWC) ash, Waste Glass, and Waste Tires for use as general highway fill. Initial studies conducted at Florida Tech concluded that MWC ash and waste glass possess engineering properties required for highway applications and the environmental characteristics were satisfactory for field deployment. The results of these studies are presented in three volumes. Volume I summarizes the findings for MWC Ash, Volume II summarizes findings for Waste Glass and Volume III summarizes findings for Waste Tires.

During this continuation study field demonstration projects using MWC ash and waste glass indicated that conventional construction methods and techniques were applicable. A comprehensive literature review was completed on the waste tires and their use as highway fill by state DOT's. It revealed that waste tires are highly compressible, but with adequate processing they can be used as highway fill.

For the field demonstration project involving the MWC ash a 82 foot (25 m) long, 32 foot (9.8 m) wide, 4 foot (1.2 m) high embankment was constructed using treated combined ash. A runoff and leachate collection system were installed for environmental monitoring. The geotechnical properties showed that combined ash exhibits high strength while being relatively free draining. An environmental analysis of 8 metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) indicated that the leachate and runoff concentrations were below surface water standards and below drinking water standards for all elements except an initial peak of selenium.

Laboratory studies conducted on combined ash from all 12 Florida waste-to-energy facilities indicated it would classify as either a well graded or poorly graded sand (SW or SP according to United Soil Classification System). The combined ash meets engineering criteria established by FDOT for use as a highway subgrade material.

The investigation of the environmental properties of waste glass revealed it can be cleaned to meet EPA drinking water standards at a reasonable cost. An outdoor reactor system was used to evaluate the environmental characteristics of waste glass leachate and waste glass cleaning methods. Prior to handling, the waste glass was crushed at a materials recovery facility. The waste glass was cleaned using two methods; direct rainfall and recirculating rinse water. Leachate from the system was analyzed for BOD5, TKN, and Phosphorus. These techniques produced leachate that initially exceeded drinking water standards, but that became clean within a reasonably short time.

For the field demonstration project involving the waste glass a 300 foot (91.5 m) section of subgrade was stabilized to a depth of 6 inches (2.4 cm) on a residential street using approximately 15% waste glass by volume. The subgrade stabilization was accomplished by mixing the waste glass with both the highly deteriorated pavement surface plus the existing base. Subgrade CBR, density and moisture contents data were collected. The construction process produced an acceptable subgrade.

Shredded tires exhibit engineering properties that are favorable for use in highway construction. They are a lightweight, free draining material, however, they undergo large initial displacements upon loading. The waste tire literature indicated that a major concern with waste tire fills was combustion. Fills in Washington and Colorado have combusted, causing numerous environmental concerns and hazards. Combustion can be avoided by proper sizing and placement. The state wide survey revealed that less than 1% of the nearly 14 million scrap tires generated yearly in Florida are available for use as highway fill. The majority of the tires are burned in either waste-to-energy facilities or in the tire-derived-fuel facility.

17. Key Words	18. Distribution Statement
Waste Glass, Highway Applications Geotechnical Properties, Leaching Properties	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	83	

Form DOT 1700.7 (8-72)

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1. INTRODUCTION

1.1 Generation Rates

There are approximately 240 million scrap tires generated annually in the United States, about 11 percent are burned as a tire-derived fuel (TDF) for heat or power generation, 5 percent are exported, and 7 percent are recycled. Of this 7 percent, about 2 percent are recycled in tire manufacturing, 3 percent are turned into rubber products (e.g., floor mats, carpet padding, etc.), and 2 percent are used as crumb rubber in asphalt pavements. The remaining 77 percent is either stockpiled, landfilled, or illegally dumped (U.S. EPA, 1994). Scrap tires make up about 1 percent of total municipal solid wastes generated annually in the United States, with an estimated 2 to 3 billion scrap tires stockpiled nationwide.

1.1.1 Availability concerns in Florida

In Florida there are 12 waste-to-energy (WTE) facilities plus a TDF plant that burn tires for fuel. Even though there is one scrap tire generated for each person in the state, burning for fuel and recycling account for over 75% of these tires. Additionally waste tires (WT) are shredded at landfills and used as daily cover.

"The Scrap Tire Management Council reported a 75.9 percent recycling rate for scrap tires in 1996, a seven percent increase over 1995... The largest segment of the recycled tires were made into tire derived fuel." Approximately five percent of the WT nationwide are processed for civil engineering applications. It may be that with the high combustion rate in WTE, refuse derived fuel, and TDF in Florida that the percentage available for civil engineering applications is less than national average.

Solid waste coordinators throughout Florida have been surveyed and asked for an indication of availability. According to the 1996 FDEP Solid Waste Report there are 158,000 tons of WT generated per month in Florida. From information received through surveys only 0.2% of the WT in Florida would be available for highway use. It does not seem economical or feasible to use WT in these applications at this time due to the lack of availability as indicated by the survey.

Even though the findings indicate that there are no tires currently available in Florida for use as fill, future research may change this scenario. This report contains a significant amount of information compiled from states with larger WT stockpiles. It includes engineering strength and environmental characteristics plus preliminary specifications that could be used as the basis of a future study.

1.1.2 Common uses

Scrap tires are currently used in the manufacturing of rubber products, pavements, sludge composting, pyrolysis for carbon black recovery, etc. There are also some alternative uses for whole tires, including erosion control, retaining walls, highway crash barriers, artificial reefs, breakwaters, and playground equipment. All these alternatives result in very limited utilization for scrap tires, and in some cases may be considered aesthetically undesirable or environmentally unsafe. Best management practices for scrap tires need to be developed so that scrap tires can be used in applications that are cost effective, environmentally safe, and engineering sound.

Using scrap tires in highway construction has been considered for over 30 years. During the early 1960s, highway applications were evaluated by the transportation industry. Crumb rubber modifiers (CRM) have been successfully used in highway pavement in many states. Mandates from the Intermodal Surface Transportation Efficiency Act (ISTEA) requires that by 1997 and each year thereafter, a minimum of 20 percent of asphalt pavement contain recycled rubber as a percentage of the total tons of asphalt (USC 23-109 Note, and 105 Statutes 1987-1990, 1991, 1994)*. An increasing amount of recycled tire rubber will likely be utilized in this application. In the long run, however, this application presents only limited consumption for waste tires. Moreover, CRM in hot mix asphalt (HMA) is expensive because of high gradation standards and the costly capital investment for processing equipment. The rubber-modified-asphalt (RMA) pavement is estimated to cost as much as 200 percent more than conventional asphalt pavement (DeGroot, et al., 1995) (King, 1995).

Potential uses of shredded tire chips as fill in highway construction were also evaluated in recent years. One appealing feature is its lightweight which could make it an attractive fill. This application could provide an alternative disposal technique to the landfilling waste tires. Approximately 11,200 scrap tires are consumed per mile for a 4" RMA pavement lift (Kennepohl, 1993); whereas, about 1.32 million tires could be used per mile for a 24" fill (Nickels, et al., 1995).

1.2 Objective

The objective of this research was to develop best management practices (BMP) for Florida's use of shredded waste tires (WT) in highway construction.

1.3 Proposed Approach

To develop BMP, the following tasks were completed:

1) the available WT fill literature was reviewed
2) basic WT chips engineering properties were identified
3) the WT chips environmental impacts were evaluated

** In response to unfavorable reactions from the States regarding the minimum utilization requirements for asphalt containing recycled rubber, the subsection addressing recycled tire rubber in asphalt pavement in ISTEA has recently been changed. So far, no such requirements were made in Section 1038 of ISTEA. Refer to National Highway System Designation Act of 1995, Public Law 104-59-November 28, 1995.*

4) the economic factors affecting the availability of scrap tire chips on the market were evaluated
5) preliminary specifications of WT for use as fill in Florida highway construction were developed

2. CHARACTERISTICS OF SHREDDED TIRES

The general characteristics of scrap tires are critical to this study. They include the physical and chemical constituents, the relative quantities and the processing equipment that is commonly used in the production of shredded tire chips.

2.1 Constituents of Tires

Rubber tires consist of three physical constituents—fabric, bead (cord) wire, and rubber compound. The relative percentage of these constituents is dependent on the type of tire construction. Each tire consists of beads, a carcass, and a tread. The three types of tire construction include bias-ply, bias-belted and radial. A tire includes approximately 80 percent rubber by weight, and the fabric and metal constituents comprise about 10 percent each.

The principal chemical elements of tire rubbers are carbon (84%), hydrogen (7%), and small amounts of nitrogen (0.2%), oxygen (2%), and sulfur (1%). It also contains some trace elements, most of which are metals. Table 2-1 indicates the elemental compositions of the residues of typical TDF with size 2" (5 cm) minus. The trace elements, such as nitrogen and sulfur, were transformed into gaseous emissions during combustion. The higher carbon content of tire rubber contributes to the relatively higher heating value of tire rubber when used as TDF. The average heating value of tire rubber is 15,500 BTU/LB, which is almost 130 percent more than coal. Tire rubber begins to ignite between 550 - 650° F, whereas, carbon starts to burn at 842° F (Stopek, 1995).

Table 2-1 Elemental analysis of TDF residues (after Stopek, 1995)

ELEMENT	BY WEIGHT AS RECEIVED (%)	BY DRY WEIGHT (%)
Zinc	1.52	1.53
Iron	2.52	2.54
Calcium	0.378	0.379
Chlorine	0.149	0.15
Chromium	0.0097	0.0087
Fluoride	0.001	0.001
Cadmium	0.006	0.006
Lead	0.0065	0.0065
Total	4.58	4.62

2.2 Categories of Tires

There are four major categories of rubber tires. The largest percentage is passenger tires, at 80 percent by number of total tires generated each year; next are truck tires at 17 percent; the third and fourth are farm equipment tires and off-road equipment tires, which make up the remaining 3 percent. Passenger tires come in rim sizes of 12 to 15 inches (30 - 38 cm), and weigh between 15 to 30 pounds (0.067 - 0.134 kN), with a generally accepted average of about 22 pounds (0.098 kN). Truck tires come in rim sizes of 15 and 16 inches (380 mm and 405 mm) for lightweight vehicles, and 15 to 24 inches (380 - 610 mm) for heavy vehicles. Lightweight truck tires weigh 30 to 60 pounds (0.134 - 0.268 kN), whereas the range is 90 to 200 pounds (0.4 - 0.89 kN) for heavy-duty truck tires (Drescher, et al., 1994). Based on the distribution of each size category, the problem of scrap tires will be primarily the disposal issue of passenger tires, which constitute the largest share on scrap tire market.

2.3 Tire Shredding

Currently, most states have legislation regulating the disposal of scrap tires. Florida landfills accept waste tires (FAC, 1995). Stringent regulations on scrap tire disposal demand advanced and sophisticated processing facilities for scrap tire shredding. Tire shredding is a BMP to produce a more manageable size and shape.

Shredder design depends upon the nature and volume of scrap tires to be reduced in size. Shredded tire chips range in size from 2 inch (5 cm) to one-quarter of a scrap tire. The size of the tire chips depends on the number of passes through the shredders, and in some cases, on the width of the knife affixed to the rotary shaft of the shredders, which can be adjusted by the operator (Astafan, 1995). High-yield shredders can ground whole scrap tires into rubber pieces that range from 2 to 8 inches, with approximate 30 to 50 tons being produced per hour.

Two types of shredders are commonly used. One is the impact type or hammermill shredder, where hammers are used to impact the tire rubber against a heavy grate. A number of hammers are fastened flexibly to an inner shaft or disk that is rotated at 1200 - 1800 rpm speeds. Because of centrifugal forces, the hammers extend radially from the central shaft. In operation, scrap tires are cut with sufficient force to crush or tear them and with sufficient velocity to keep them from adhering to the hammers. They can be further reduced in size by being struck against breaker plates or cutting bars fixed around the inner periphery of the inner chamber. In the hammermill, chip size is controlled by the opening in the grate, which can be changed to meet the needs of the end-product. The cutting action continues until the chips are of the size requirements and fall through the grate at the bottom of the mill.

The other type of shredding process uses shear forces to cut scrap tires. The shear shredders usually operate at low speed (10 - 30 rpm). They have counter rotating shafts with knives, or knife rotors affixed to the shafts that overlap the opposing knife to cause a scissors-like shearing action. This type of shredder gives much cleaner cuts on the edges of tire chips. Tire chips produced by shearing action reduces exposed reinforcement and are preferred for highway construction.

If the metal has to be removed from the tire chips, such as in processing tire rubber used as TDF, CRM, etc., the scrap tires must go through some preprocessing equipment before shredders. The preprocessing equipment usually includes the debeader which cuts the bead section of a whole tire leaving the bead encapsulated with rubber, and the bead stripper, used to strip the bead wire cleanly from the tires. Bead wire is recovered as scrap steel.

At present, scrap tires used in highway construction does not have to be free of metals. They are, therefore, obtained directly from the shredding facilities that were originally designed for the landfilling of shredded tires. But for BMP to be met, it is suggested that the shearing-type shredders be used for processing WT for highway fill.

3. ENGINEERING CONSIDERATIONS OF SCRAP TIRES IN HIGHWAY APPLICATIONS

A general review of the major highway projects and field demonstration test sites incorporating shredded WT and the case studies are summarized below.

3.1 Applications of Scrap Tires in Highway Construction

The application of turning scrap tires into crumb rubber for use in hot-mix asphalt concrete is not a new concept. As early as 1960s, the possibilities of using reclaimed WT rubber in asphalt compositions were evaluated (Bloomquist, 1993). By using readily available rubber from scrap tires, asphalt paving mixes were improved, especially for low-temperature performance. Crumb rubber asphalt is not the focus of this research and is summarized simply for completeness.

Varieties of highway-oriented products and safety devices made from recycled tire rubber have been developed and used in some highway projects. These products include, but are not limited to, noise abatement walls, crash protection barriers, paving stones, railroad crossing mats, portable speed bumps, and retaining wall blocks. These products have limited applications, primarily because of either cost or performance concerns.

In California, three trial projects were initiated to evaluate possibility of using scrap tires for erosion control. One project was the installation of waste truck tires in an embankment to control shoulder erosion. Another project was the installation of waste truck tires in a low velocity drainage channel with highly erodible soil to control slope erosion. The testing results indicated that using scrap tires for erosion control or highway maintenance may provide an immediate and economical solution for small projects initiated by maintenance personnel. Waste tire barriers provided temporary windbreaks for establishing Tamarisk trees. This project was not cost-effective because it was extremely labor-intensive. Although temporary protection for the trees and the roadway, and provided for large utilization for waste tires (Williams, et al., 1987).

Using shredded tire chips as aggregate in base and subbase courses was investigated. The key objective was to make shredded tire chips a favorable insulator against frost penetration, because of their low thermal conductivity. A test strip of WT chips beneath an unpaved road in Richmond, Maine showed a reduction of frost penetration of up to 40 percent (Eaton, et al., 1994).

The application of shredded tire chips as lightweight fill in highway embankment construction is a relatively new perception. Considering the large-scale utilization benefits from this application, researchers are making efforts to study the engineering effects and environmental impacts. Several states, including Minnesota, Wisconsin, Oregon, Vermont, Virginia, Washington, etc., have built embankments using shredded tire chips as fill. These projects are currently being evaluated and will provide useful data for many state highway agencies.

Waste tires have been used in many potential highway construction applications. Table 3-1 summarizes these potential applications.

Table 3-1 Typical applications of scrap tires in highway construction

Scrap Tire Description	Application(Kennepohl, 1993)
	1. Structural Use:
SWT	lightweight fill in embankment construction
SWTR	retaining wall blocks
SWT	base course aggregate
	2. Non-structural Use & Highway Safety Products:
SWTR	energy attenuators (crash barriers)
CR	noise barriers
SWT/WST	retaining wall backfill, blocks
SWTR	ballast for construction markers
SWTR	guide rail block-outs/posts
SWTR	portable speed bumps
CR	railroad crossing mats
WST	utility access hatch transition collar
	vehicle protection barrier
	3. Pavement:
CR	rubber modified asphalt
CR	Portland cement concrete aggregate
SWTR	paving stone
CR	crack sealant
CR	stress absorbing membrane (SAM)
CR	stress absorbing membrane interlayers (SAMI)

SWT = shredded waste tire
SWTR = shredded waste tire rubber
WST = whole scrap tires
CR = crumb rubber

3.2 Shredded Tire Chips as Fill in Highway Construction

Historically, lightweight materials have been employed in weak soil areas like bog or muck subgrade soils. By using lightweight fills the road section is floated over the poor soils. Traditional waste lightweight fill materials are timber scraps such as wood chips, sawdust, and tree barks. Other lightweight fill materials include foamed concrete and expanded polystyrene (EPS). Shredded scrap tires, being a lightweight fill, could also be used in these applications. Traditional waste lightweight fill materials were commonly used in rural and secondary roadway construction. The expected compacted densities of these lightweight fill materials and their major features are described in Table 3-2. Shredded tires and wood chips have similar characteristics. Both have unit weights in the 20 to 40 pcf (3.15 to 6.30 kN/m^3) range, both are readily available and both have been used in field trials. The foamed concrete and EPS are more costly, yet yield benefits not found in waste materials, while being suitable for specialized cases.

Table 3-2 Major features of lightweight fill materials

Lightweight Fill Material	Expected Compacted Density (pcf)	Features
1. shredded tires	20-45	(1) readily available (2) considered a by-product, relatively inexpensive (3) easily placed by standard construction equipment (4) design parameters based on field trials (5) restricted use below groundwater table
2. wood chips	24-36	(1) readily available (2) easily placed with standard construction equipment (3) limited to use in saturated zone at all times (4) considered a by-product, relatively inexpensive (5) design parameters based on field trials
3. foamed concrete	24-80	(1) limited number of suppliers (2) specifically designed and manufactured for each case; high cost (3) placed with special equipment (4) high compressive strength (5) little horizontal pressure exerted on adjacent structures (6) design parameters available
4. EPS	3	(1) the lowest available density for the strength it supplies (2) easily placed, no need for additional equipment (3) little effect from environmental conditions such as submersion (4) the least amount of soil replacement required for given load reduction (5) formal design parameters available (6) high unit cost

3.2.1 Effects of Shredded Tires on Asphalt Concrete Pavement Performance

A flexible asphalt concrete (AC) pavement usually consists of an AC pavement layer, a base and/or a subbase layer, and subgrade. Gharegrat (1993) established a finite element (FE) AC pavement model that contained an AC pavement layer overlying a subbase layer, then a tire-chip fill layer, and subgrade. The model was developed using the MICH-PAVE computer software. The AC was modeled as linear elastic, the other layers as nonlinear and cohesionless. To estimated moduli for nonlinear layers, stress-dependent relationships were used, while the modulus of AC was assumed to be 300,000 psi (2.1 mPa). The thickness of each layer was defined in the model calculations. A 6-inch (15 cm) AC layer and a 24-inch (60 cm) subbase were used while the subgrade was varied from 0 to 96 inches (0 to 240 cm). The FE analysis was conducted on one cross-section of the pavement containing a tire-chip layer and a control section without WT chips. The objectives of the analyses were to examine the pavement performance under different layer thicknesses and compare the WT pavement with the conventional pavement. Gharegrat (1993) developed recommendations on the minimum depth requirements for the AC layer, subbase layer overlying WT chips, and the appropriate depth of WT chips. Pavement deflections under the center of the load and tensile strains at the bottom of the AC pavement were used as the main criteria for the evaluations of pavement responses. The loading parameters assumed in the FE analysis were a static load equivalent to 9.0 kips; a tire pressure of 100 psi and a radius of loaded area equal to 5.35 inches.

FE analysis indicated that for flexible pavement with WT chips in the subgrade, the major factors affecting the resilient deformations in the pavement were:

(a) the thickness of tire chip layer
(b) the thickness of AC layer
(c) the modulus of AC layer
(d) the thickness of granular subbase

(e) the resilient modulus of the subbase and subgrade

All these factors were used as input parameters in a FE sensitivity analysis of the pavement response. The effects of using waste tires beneath an AC pavement are as follows:

1) The WT chip layer thickness has more of an effect on resilient deformations than cover thickness, while the effect of WT chips on tensile strains in the AC layer was not significant. Reducing the WT chip layer thickness from 48 to 24 inches reduced the resilient deformations by almost 50 percent; however, doubling the cover depth between the load and WT chips only reduced the deformations by 22 percent.
2) The AC modulus significantly influences the tensile strains, but has little effect on the resilient deformations. Higher AC moduli yielded much lower tensile strains.
3) A thickness of 6" AC layer was found to effectively control the resilient deformations, but AC thickness below 6" sizably increased the resilient deformations.
4) Subbase thickness is much more important in reducing tensile strains in the AC pavement containing a WT chip layer than in a conventional pavement. However, the difference between the tensile strains in both cases was not significant when the subbase thickness exceeded 24 inches.
5) The type of subbase and the type of subgrade show negligible influences on the deflections and the tensile strains in the pavement. The only exception is that when the silty sand subbase was used, the effect of subbase modulus on the resilient deformations was significant.

Humphery (1996) reported that a 6 ft (180 cm) thick soil cover above 2 ft (60 cm) of WT fill layer would provide sufficient overburden to yield acceptable performance of the AC pavement. The deflections and the tensile strains were nearly the same as those from the control section.

3.2.2 Effects of Shredded Tires as Backfill in Retaining Walls

Another important application of scrap tires is in earth retaining structures. In this case, WT chips replace traditional backfill to reduce lateral pressures against the walls yielding a substantial saving in construction cost. This application may be used in lieu of other retaining wall structures, such as mechanical stabilized earth retaining walls.

Only a few applications of shredded WT chip backfill in retaining walls were reported. Humphery (1996 [a]) reported that the lateral pressure against a 14 foot (4.3 m) high retaining wall with WT backfill plus 750 psf (36 kPa) surcharge was less than one-half of the lateral pressure of soil backfill (Humphery, [a] 1996). This reduction in lateral pressure becomes very useful in situations where either the construction cost or the available backfill soil becomes a limiting factor.

Because WT backfill is cohesionless and granular, both Rankine and Coulomb theories can be used to estimate lateral earth pressures against the wall. The major difference between the two theories is that Coulomb accounted for the effects due to the shape of the wall stem, plus the friction between the wall and backfill. This approach may more closely simulate field conditions. Rankine assumed that the wall stem has no effect on the shear stress of the soil (Newman, 1981). Therefore, using Rankine's theory in retaining wall design would tend to give more conservative results.

Besides the lateral force reduction from its lightweight, another beneficial effect arising from WT is its relatively high frictional strength. According to Edil, et al. (1992), the typical value of the frictional angle should be assumed to be around 45°. Angle of internal friction of conventional soil varies between 26° and 38° (Liu, et al., 1987). The high friction angles of WT reduce the lateral force on the walls. The combined effects of the lightweight material and high friction angle of the WT backfill in retaining wall structures result in more than 50 percent reduction of lateral force compared to traditional soil backfill. Both field and calculated results are in agreement (Humphery, [a] 1996).

3.3 Construction Methods and Problems

Various projects were constructed as demonstrations to gather design and specification data, or to solve specific engineering problems such as large settlement of roadways, landslide repairs, embankments over soft foundations, and stability reinforcement. Seven states nationwide have constructed highway projects using WT chips as fill material (Humphery, [b] 1996). The common features of these field sites are summarized below.

WT chips used as lightweight fill were produced from any type of scrap tires. Chip sizes were not critical. Usually, chips no less than 4" were used for the benefit of the decreased processing cost.

All WT chip fills were placed above the seasonal high groundwater table to mitigate the possible environmental impact of leachate from WT chips on groundwater. In some projects, WT chip fill was even placed over a wood chip layer to separate WT chip fill from the subgrade soil. Almost all WT chip fills were encapsulated in geotextiles to prevent any migration of surrounding soils into the WT chip fill and increase the integrity of the fill layer and the stability of the highway structures. Projects with lightweight fill of WT chips placed up to 50 percent by volume when mixed with soil, or as a separate layer were demonstrated.

Conventional tracked construction equipment was better for handling WT chips. Due to occasional flat tires caused by extruded wires from WT chips, pneumatic-driven vehicles should be avoided. The handling and placement of WT chips possess no particular difficulty when compared to the conventional granular fill materials. Compaction energy was not critical, and static compaction can be used. Compaction control was generally monitored by full coverage passes of compaction equipment.

Common problems encountered in these projects include excessive settlements and pavement deflections. These problems may be associated with deficiencies in design, such as insufficient ratio of soil cover over WT fill, a very thick WT layer, extremely large sizes of WT chips, and insignificant compaction of the WT layer. Large-scale initial compression of the WT layer upon loading was a result of the low-strength of WT chips.

There were a few occurrences of fire hazards on WT fill roadways, adding the complexities to its lightweight fill application. Fire hazards have always existed in open-dump disposal and scrap tire stockpiles. This issue will be covered at length in the following chapter.

A detailed summary of these projects is shown in Appendix A. Special case histories are detailed in Appendix B.

3.4 Engineering Properties of Shredded Tires

The physical and basic engineering properties of shredded tire chips have been studied by many researchers. Typical data reflecting the engineering behaviors of tire chips were collected from different sources.

3.4.1 Gradation

Scrap-tire processing technology has developed to meet new specifications, making it possible to generate a greater supply of shredded tire chips, with various sizes and consistencies for targeted end uses. Compared to CRM, the size requirement for the use of shredded tire chips as fill material in highway construction is not as critical. Coarser and larger scrap tire chips, without metals being removed, can be used as fill as long as some consistencies are maintained. The use of tire chips between 2" (5 cm) and one-quarter of a tire as lightweight fill in highway applications has been well documented (Engstrom, et al., 1994). However, the sizes of commonly available tire chips range from 2" (5 cm) to 12" (30 cm). Tire chips falling in this range can be effectively placed as fill in highway embankments.

3.4.2 Unit Weight

The average unit weight of shredded tire chips is approximately one-fifth that of conventional soil unit weights (Newcomb, et al., 1994). Although tire chips are broadly considered as lightweight fill, their unit weight covers a relatively wide range, and varies appreciably case-by-case. There are many factors affecting the unit weight, including the shredding processes, whether or not a pre-cut process was used, sizes of the product with or without metals being removed, and the extent of metals recovered.

Stockpiled shredded tire densities also vary, based upon factors such as height of the pile, size of the tire chips, time of exposure, placement method (conveyor, backhoe), and compression due to vehicles on piles. They are also affected by the stockpile angle of repose, weather (such as ice, rain, snow), and vibration during transport. The Texas Natural Resource Conservation Commission (TNRCC) chooses to use an average stockpile density of 35 lb/ft^3 (5.5 kN/m^3), but actual stockpile density can vary from about 20 lb/ft^3 (3.1 kN/m^3) at the top of the pile, to about 60 lb/ft^3 (9.4 kN/m^3) at the bottom of a 20 ft (6 m) pile. Additionally, the types of tires, such as steel-belted or glass-belted, have a slight effect on unit weight.

Shredded tire chips can form substantial porous spaces because of their rough surfaces and high degree of irregularity. The chip size causes significant differences in bulk unit weight. Unit weights varying from 14.5 pcf (2.3 kN/m^3) for maximum size 12" x 12" (30 cm x 30 cm) to 30 pcf (4.8 kN/m^3) for 2" (5 cm) minus shredded tire chips were reported in the previous studies (Newcomb, et al., 1994). A similar study in Maine indicates that 2" (5 cm) tire chips have an average unit weight of 25 pcf (3.9 kN/m^3) (Manion, 1992). Laboratory testing at Florida Tech for 3/8" (1 cm) minus samples with all metals recovered, yielded an average uncompacted density of 31 pcf (4.9 kN/m^3).

Typical bulk unit weights of shredded tires are summarized in Table 3-3. The size of shredded WT chips used ranges from 3/4" and 24", with the average size being about 7", and the bulk unit weight generally increased with reduced size of tire chips.

Compaction does not always seem to increase the density of shredded tire chips, especially for larger chips. In a demonstration project in Wisconsin, 18" top size tire chips were used as lightweight fill, the compacted density only reached 19 pcf, which was slightly higher than its bulk unit weight.

Compaction of shredded tire chips does not follow Proctor's moisture-density relationship. This behavior may result from the non-existence of pore water to form the liquid films around the chips. It makes conventional density controls, such as relative compaction, inapplicable for evaluating shredded tire chips in field construction. This may imply that some other means needs to be found to control the field-density of WT chips during construction. In general, the factors affecting compaction of tire chips are; compaction methods, tire chip sizes, lift thickness, chip/soil ratios when used as rubber soil, and in laboratory testing, the size of compaction mold (Ahmed, 1993).

Manion (1992) used 2" minus shredded tire chips for compaction studies. He employed three different compaction energy levels (i.e. modified and standard Proctor, and 60 percent of standard Proctor) on these samples. Test results for these compacted samples gave densities between 38 - 42 pcf, or about 10 percent variation in density from the lowest selected compaction energy to the highest, which was equivalent to an increase of compactive efforts by about 6.5 fold (Manion, 1992). In a parallel study Ahmed (1993) also indicated that there were no significant effects on the density of pure tire chips due to the change of compactive efforts. Based on these findings, it is expected that in field construction only a modest compactive effort is required to achieve the maximum density of tire chips. (Ahmed, 1993).

Table 3-3 Summary of chip sizes and unit weight of shredded tires used as highway fill

NO.	CHIP SOURCE (OR PROJECTS)	CHIP SIZE (in)	UNIT WEIGHT (pcf) (uncompacted)	(compacted)
(1)	(2)	(3)	(4)	(5)
1	Caltrans	2 x 2	27 - 31	N/A*
2	Caltrans	2 minus	26 - 35	N/A
3	ATR, Florida	3/8 (no metal)	31	33
4	Brevard, FL	2 x 6	37	N/A
5	Maine: Field Trial	3 - 12	25	38 - 43
6	Minnesota: lab test 1	12 x 12	14	22
7	Minnesota: lab test 2	1.5 minus	31	N/A
8	Minnesota: lab test 3	3/4 - 2	35 - 30	N/A
9	Minnesota: Prior Lake	4 - 6	22	N/A
10	Oregon, Landslide Proj.	max. 24	30	45
11	Virginia: Road Ramp	max. 10	25	N/A
12	Wisconsin: field demo.	4 x 18	19	19
	Average:	7	26	33
* Not Available				

The effects of shredded WT on compacted densities were also investigated through a field demonstration project in Wisconsin (Edil, et al., 1992). Three distinctive sizes of shredded tire chips were selected for a test embankment construction. Tire chip samples with an average top size of 2.5" and 1" had compacted densities of 25 - 35 pcf respectively; but tire chip samples with an average top size of 12" were only slightly densified, compared to their loose density of 19 pcf. This result was obtained even though the coarser chips were confined with an additional overburden stress of one foot of soils (Edil, et al., 1992).

Compacted density of WT chips can be determined by the volume change method. Theoretically, the compacted density is equal to the initial density (bulk unit weight) multiplied by the change ratio of volume induced by compaction. That is

$$\rho_c = \rho_0\left(\frac{V_0}{V_c}\right) = \rho_0\left(\frac{H_o}{H_c}\right) \qquad (3\text{-}1)$$

where ρ_c is the compacted density of concern; ρ_0 is the initial bulk unit weight of tire chips, and (V_0/V_c) is the volume change ratio after compaction. It can be calculated by knowing both the initial thickness (H_0) of the shredded tire layer and the layer thickness after compaction (H_c). The change in layer thickness of shredded tire chips is the vertical compression induced by compaction. This compression extent may be used as a parameter in field construction for the density control of the tire chips.

3.4.3 Specific Gravity

The specific gravity of tire chips ranges from 1.01 to 1.05 based on tests conducted according to AASHTO 785-85 for 2" (5 cm) tire chips (Manion, 1992). CalTrans has reported values between 1.06 to 1.15 for tire chips less than 2" (5 cm)

(Drescher, et al., 1994). For the samples obtained from ATR, in Jacksonville, Florida, the specific gravity for the tire chips 3/8" minus measured according to ASTM C127 was 1.04, which falls into the range of similar studies. Variation of specific gravity are dependent on the percentage of metal and fabric present.

3.4.4 Permeability

Shredded WT's exhibit high porosity, reportedly in the range between 50 and 80 percent (Drescher, et al., 1994). This characteristic also provides a high permeability. Studies show that the permeability of 1" tire chips varies from 0.54 cm/sec to 0.65 cm/sec with compactive effort decreasing from the equivalent of a modified Proctor to 50 percent of standard Proctor (Manion, 1992). In a similar study by CalTrans, shredded WT with 100% passing the 2" sieve size. The permeability coefficient obtained was about 3.5 cm/sec, or about 20 to 30 times higher than the permeability of a typical granular base (Newcomb, et al., 1994).

3.4.5 Compressibility

Compression tests on large diameter chips are very difficult. To date, one-dimensional compression testing on both small-diameter WT chips or chip-soil mixtures was performed to measure the compressive behavior of WT chips in limited cases. For WT chips less than 2" (5 cm), the average compressibility (C_c) and rebounding (C_r) indices were measured at 0.5 and 0.27, compared to 0.35 and 0.03 for wood chips (Newcomb, et al., 1994). Typical C_c and C_r for normally consolidated clays with low to moderate sensitivity range between 0.4 and 0.02, respectively (Holtz and Kovacs, 1981). The testing results indicate that the compression index of WT chips is similar to clays.

It is typically assumed that there are three mechanisms to explain the compression behavior of the WT chips. One is the minor compression from rearrangement and sliding of chips, occurring mainly during the first loading cycle, and is mostly irrecoverable. The second is the major compression caused by bending and flattening of the WT chips, which is mostly recoverable upon unloading. The last compression is induced by elastic deformation of the WT chips, which is very small, occurring generally at stresses 20 psi or higher, and is totally recoverable (Ahmed, 1993).

The BMP for solving the compressibility concerns of WT can be addressed by increasing the overburden pressure or filling the air voids with materials less compressible than WT chips, such as sand or clay. In the case of using tire-chip-soil mixtures, laboratory testing indicated that approximately 40 percent of the WT chips by weight is an optimum mixing ratio. Above this percentage, the compression of the mixtures will be controlled by the tire chips because there are not sufficient soil particles filling the void spaces of the WT chips (Ahmed 1993).

3.4.6 Elastic Behavior

The elastic modulus of WT chips is stress-level dependent and much lower than moduli for other granular soils. The elastic modulus of WT chips less than 2" were calculated at 113 psi (280 kPa) and Poisson's ratio at 0.45 (Newcomb, et al., 1994). Laboratory testing on WT chips less than 2" revealed that the range of elastic moduli at a secant of 10 percent vertical strain was between 9 - 25 psi (62 - 173 kPa). The elastic modulus and Poisson's ratio for typical sands range between 10,000-25,000 psi (69,000 - 172,500 kPa) and 0.15-0.35 respectively (Das, 1995).

Generally, WT chips can be characterized as a low-strength granular material. This behavior may have a negative impact on the use of tire chips as lightweight fill because of its adverse effects on flexible pavement deflection (Manion, 1992).

3.4.7 Shear Strength

The shear strength of 2" (5 cm) WT chips has been studied by CalTrans. The apparent cohesion and the internal angle of friction were reported to be about 4.2 psi (29 kPa) and 18°, respectively (Drescher, et al., 1994). The angle of repose, measured from the tire chip stockpiles in Minnesota, was estimated to be 45° (Drescher, et al., 1994). A parallel study in Wisconsin gave a range for loose tire chips between 37° and 43°, and a value for compacted tire chips as high as 85° (Edil, et al., 1992). These values imply that compacted WT chips exhibit excellent friction characteristics.

3.4.8 BMP for Engineering Properties of Shredded WT Chips

Shredded WT chips can be categorized as lightweight coarse granular materials that can potentially be used as highway fill. The typical gradation curve has a wide range of particle sizes.

The bulk unit weight of WT chips is about one-fifth that of conventional soils. This physical property will vary as a function of the size and shape of the shredded WT product. There is also an inverse relationship between size and strength, implying that larger diameter specimens would fail at lower stresses than smaller pieces (Bligh, et al., 1995). In the handling and placement of WT chips, bulk unit weight and compacted density can be used. Due to the high compressibility of WT chips, even in loading, hauling, and in placement, measurement by weight is deemed to be the best practice. Unlike conventional fill, moisture has no effect on the compaction behavior of WT chips. Compaction control has to be monitored in terms of WT chip layer compression instead of relative compaction.

Shredded WT chips have a compression and rebound indices similar to conventional soils. In field placement, initial settlement can be expected to be substantial. It is the main portion of total settlement. Tests have shown that this initial compression can be as high as 80 percent of the uncompacted WT fill depth in extreme cases (Roberts, et al., 1996). Elastic properties of Shredded WT chips are nonlinear and the material is cohesionless. The resilient modulus of shredded WT chips is so low that it may preclude its use as fill materials unless deflection of the pavement has been properly addressed. WT chips also exhibit high friction behavior. Using reinforced soil with shredded WT chips will enhance slope stabilization in highway embankment construction. Using mixtures of WT chips with soils in placing fill layers is also expected to improve compressive behavior of WT chips, and in turn to improve performance of AC pavement system.

3.5 BMP of Using WT Fill in Highway Construction

WT chips should be used in nonload bearing engineering situations whenever possible. WT chips are biologically stable, and therefore, would maintain their integrity when used as fill. Their lightweight, free-draining, excellent-friction characteristics can be advantageous for improving weak subgrade soils, decreasing frost penetration, repairing landslides, controlling soil erosion, and for use as retaining wall backfill.

In handling and placement during roadway construction, no special equipment was required. Conventional construction equipment can be used to construct WT fill just as other bulk fill without particular difficulties.

Using WT chips as fill materials does have certain drawbacks. One basic problem is the lack of the specifications and design standards to guide the proper application of this material. A second difficulty arises from the fact that there are no standard testing methods to evaluate its mechanical properties.

For the size requirement, two factors need to be considered. One is processing cost, and the other is the acceptable size for shredded WT as fill. The shredding cost is directly proportional to the energy consumption. Chipping tires to sizes below 1" is not considered cost-effective, whereas, allowing chips larger than 24" poses engineering performance problems. Proper sizing of the chips will bring down construction cost, and make handling and placing less difficult. For these reasons, shredding WT into 4" to 12" chips is practical for this product to be used as fill in highway projects.

In developing a BMP for using WT fill in highway construction, it should be noted that WT chips do require proper preparation before they can be used. The scrap tires should have edges relatively free of metal. This requires proper quality control during shredding. A shear type shredder would produce the cleanest edges for this material. To minimize the impacts of WT on the environment oils must be cleared from the WT. The reports about the leachate are still inconclusive, but their are in favor of using the fill in highway construction.

3.6 Potential Applications of Shredded WT for FDOT

With the increasing population in Florida, more highways are being constructed. WT chips may find applications as fill in Florida highway construction to serve as an alternative road-building material. Considering the geological and hydrological features in Florida, there are several approaches to use WT fill in FDOT projects.

First of all, applying WT chips to the base or subbase layer to minimize frost heave does not prove to be practical, because on the whole, Florida is not in a severely cold or frost-affected area, even in northern Florida. There is a potential for mixing granular soils with WT chips in open-graded course to improve drainage and help distribute stresses in flexible pavement systems. This would more than improve the performance of pavement, conserve the natural soils, reduce highway maintenance, and more importantly, convert a waste material into valuable resources.

Out of concern for the leaching behavior in using WT fill, the shallow groundwater levels commonly existing in Florida almost preclude the fill application of WT chips in cut-off highway embankments. In some low-lying terrain or hilly regions, there is the potential for WT chips to be used as subgrade fill, either by mixing them with other soils or placing them as a separate fill layer. For such fill applications, disposal of high-volume scrap tires can be realized.

At present, WT chips as lightweight fill can be used in FDOT highway projects on a test basis. For collection of construction data and development of design and construction specifications, test embankments and retaining walls should be constructed to incorporate WT chips as fill, which would otherwise go into Florida landfills. This will provide a positive application of alternative waste materials in highway construction and also help develop BMP for scrap tire disposal in Florida. In some FDOT highway ramps, small-scale test projects using WT chips or WT chip-soil mixtures in the replacement of bulk fill can also be undertaken. For this purpose, some construction data and specifications from other states, such as Virginia, Oregon, Minnesota, Washington may be referred to in FDOT applications at the current time, because of the lack of local information about the lightweight fill application of WT chips.

For other road projects, like unpaved roads, secondary roads, and low-volume driveways, WT chips can be directly put into the application to replace conventional fill materials. The possibility of crumb rubber from scrap tires used in pervious parking pavement should also be considered and put into effect on a trial basis.

4. ENVIRONMENTAL ACCEPTABILITY AND CONCERNS

Environmental concerns of using WT fill in highway construction include the possible pollution caused by WT leachate in the fill and the potential for fire resulting from WT fills. In the United States, several states have already performed studies evaluating possible toxic-leachate from WT fills.

4.1 Toxic-Leaching Behaviors of WT Fill

4.1.1 TCLP Studies

In 1990, Radian Corporation in Austin, Texas conducted a laboratory study for the Rubber Manufacturers Association to assess what compounds may be leached from representative cured and uncured rubber products. Radian used the then-proposed EPA Toxic Characteristic Leaching Procedure (TCLP) test, plus the then-current Extraction Procedure (EP) Toxicity test on cured, uncured, ground, and unground rubber products.

The results showed that leachate from the tire samples contained the metals barium, chromium, lead, mercury and the organic compounds toluene, phenol at concentrations from one to three times less than proposed TCLP regulatory levels and U.S. EPA Drinking Water Standard MCL values.

4.1.2 EP Toxicity Test

By using Extraction Procedure Toxicity Test (U.S. EPA 1986), a WT rubber sample was extracted with 0.5N acetic acid with a pH of 5 ± 0.2, and the extracts of the WT rubber were analyzed by Inductively Coupled Plasma Spectrometry (ICPS). The levels of Ag, As, Ba, Cd, Cr, Hg, and Se were well below EPA toxicity levels. Therefore, it is concluded that these constituents existing in WT (crumb) rubber are not hazardous.

4.1.3 Leachate Studies in Minnesota

In 1989, Minnesota Pollution Control Agency (MPCA) contracted with Twin City Testing Corporation, Inc. to determine if there was a cause for concern of leaching of metals or poly-aromatic hydrocarbons (PAHs) from waste tires. During the testing, the WT chips were exposed to aqueous media having pH ranging from 3.5 to 8.0 to investigate possible leaching. In addition, soil and groundwater samples taken from two existing WT sites and a stockpile were analyzed and compared with the parallel laboratory studies. The major findings from these studies are summarized below (Engstrom, et al., 1994):

1. Toxic metals were leached, in the highest concentrations, from the tire samples under acidic conditions (pH = 3.5). The constituents of concern are barium, cadmium, chromium, lead, selenium and zinc.
2. PAHs and Total Petroleum Hydrocarbons were leached from WT in the highest concentrations under alkaline conditions (pH = 8.0). Constituents of concern included carcinogenic and noncarcinogenic PAHs.
3. WT chips did not leach contaminants of concern in neutral solutions (pH=7.0).
4. Drinking Water Recommended Allowable Limits (RALs) set up by the Minnesota Department of Health may be exceeded by WT leachate under extreme pH conditions for certain parameters. These parameters include arsenic, barium, cadmium, chromium, lead, selenium, carcinogenic, and non-carcinogenic PAHs.
5. The metals leached from waste tire stockpiles were similar in concentrations to those leached in areas where WT were used for fill.

Based upon the results of this study, MPCA developed a policy that requires that WT chips not be submersed in water or used in pH environments less than 3.5 or higher than 8.0.

MPCA was also contracted to conduct chemical stability testing of retaining wall blocks (2' x 2' x 4') made from WT by Multi Block, Inc. The blocks were exposed to liquid solutions with varied pH (acid-base) levels, then the leachate was analyzed for heavy metal content (arsenic, barium, cadmium, chromium, lead, mercury, selenium and silver), total petroleum hydrocarbons, and PAHs. Test results showed that the contaminants were not present in the solutions after exposure (Arlig, 1995).

4.1.4 Leachate Studies in Wisconsin

The Wisconsin State Laboratory of Hygiene evaluated the potential environmental problems of using WT chips in highway projects, by conducting duplicate EP toxicity tests on WT samples. The results showed detectable but very low release patterns for all substances tested and a declining concentration with continued leaching for most constituents (Edil, et al., 1992).

Hardness, anions and organic indicators such as Cl-, SO42-, BOD, and BOD/COD ratio, NO2-NO3- and TKN, and metallic elements like lead and sodium, showed rapidly decreasing concentrations between the first and second elution. This declining pattern implied that these constituents may come from the surface coatings of tires instead of their compound structures. Throughout the testing, the WT chips appeared to release no base-neutral regulated organics. Four metallic elements (Ba, Fe, Mn, and Zn) exhibited increasing concentrations with continued leaching. This pattern implied that these constituents are mainly being extracted from the mass of WT chips rather than from a surface coating (Grefe, 1989).

The highest concentrations for Fe and Mn were at or above their applicable drinking-water standards (mcl = 0.3 mg/L for Fe, and mcl = 0.05 mg/L for Mn) (mcl: maximum concentration level), while those for Ba and Zn were about one order of magnitude below their standards (mcl = 1 mg/L for Ba, and mcl = 5 mg/L for Zn). In general, WT leachate data indicate little or no likelihood for environmental groundwater problems.

Environmental field studies were also conducted by the University of Wisconsin. The results from the field testing are summarized below (Edil et al., 1992):

1. The WT leachate analysis indicates no significant leaching for most constituents of concern, such as lead and barium. The pH of the leachate indicated slightly alkaline conditions (7.3 to 7.9), which conforms with the findings from Minnesota.
2. The leachate samples contained elevated concentrations of organic compounds represented by COD and BOD, but the concentrations declined rapidly. It is believed that WT chips may have contributed organic substances to the leachate solutions, but are not likely to be responsible for the continuous presence of these compounds.
3. The abrupt elevated concentrations of cationic parameters, such as conductivity, hardness, calcium, and magnesium, as well as anionic parameters like alkalinity, chloride, and sulfate can be attributed to other sources instead of the embankment with WT chip fill. The road dust treatment by application of calcium chloride was likely the reason for high concentrations of these compound.

The results from both laboratory and field tests indicated that WT chips leached very small amounts of contaminants compared to other wastes. The leaching behavior does not indicate that the use of WT in highway construction would constitute a threat to groundwater or surface water. WT should be carefully placed in locations above the high water table and be kept out of contact with any water bodies, and they should be restrained from being used where high acidic or basic environments exist. Their use as lightweight fill in highway structures should continue to be reviewed on a case-by-case basis (Grefe, 1989).

4.1.5 Leachate Studies in Ontario, Canada

Laboratory tests were conducted based on the Ontario Regulation 309 acetic acid leachate extraction procedure. Three extract samples of WT chips were analyzed, and the data were compared to the parameters contained in Schedule 4 of Regulation 309-Acidic. Distilled water leachate testing on three samples of WT chips was completed by Zenon Laboratories of Burlington. The WT chips were subjected to a distilled water leachate procedure. These criteria follow listed the Ontario Drinking Water Objective (ODWO). The preliminary results of leachate analyses indicated that the WT chips remain essentially inert (Kennepohl, 1992). Therefore, it was concluded that the development and evaluation of a variety of WT chip soil mixes for the lightweight fill should continue.

4.1.6 Leachate Studies in the United Kingdom

Experimental studies to examine the effects of toxic-leaching from waste tires on the marine environment were conducted in the United Kingdom. The materials were very fine crumb rubbers, processed from retreaded tires to simulate a "worst case" study caused by the increased leaching rates and leachate concentrations under high-surface-to- volume ratios. Samples of unpolluted seawater/crumb rubber mixtures were shaken continuously in a circular motion at 100 rpm for up to three months. The analysis of leachate solutions found (Collins, et al., 1994):

1. In all leaching studies, a decrease of 1 pH unit was observed. This decrease was probably due to the acidic resins added as surfactants by the tire manufacturer.
2. The only heavy metal detected in the seawater leachates was zinc. Other metal concentrations, including cadmium, copper, chromium, lead and nickel, were below detection limits (Cd ≤ 0.01 ppb; Cu, Cr, Pb, Ni ≤ 0.05 ppb).
3. The zinc concentrations in seawater leachate showed the following release pattern: leachate concentration was directly related to size of crumb rubber tested; doubling of the size fraction resulted in a halving of the release rate

corresponding to halving the surface area of tire rubber. The leaching of zinc from tire rubber was believed to come from the outer surface, and attributed to larger quantities (1-2%) of zinc oxide used in tire manufacture to assist the vulcanization process.

4. There was not much leaching of zinc from tire rubber in seawater, because it usually maintains a pH of 8. In addition, zinc in seawater provides an essential element for the growth of many organisms.
5. The leachate was analyzed by fluorescence scanning to assess the organic content. The results indicated that a range of single to multiple benzene ring compounds were present in the leachate. The polyaromatic hydrocarbons (PAHs) present, although not characterized, were likely to be derived from the process oils used in tire manufacturing. The total release after 75 days was estimated to be about 5 mg/tire.
6. The biomass study indicated that the dilution of the tire rubber leachate would not to have a significant effect on the growth rates of the specific phytoplanktons: Phaeodactylum and Isocrysis.

Further studies were suggested to analyze organisms growing on waste tire reefs to determine if there was evidence for bioaccumulation of these leached tire contaminants. This study provided additional evidence that under neutral-basic environments, most heavy metals are not readily leached out from scrap tires. This finding agrees with what was observed in the leachate studies in Minnesota. It also indicated that large WT chips have lower leaching rates than small WT particles.

4.2 DTA (AB-DTPA) Test

The WT rubber was also tested for bioavailability and toxicity of elements using the ammonium bicarbonate test, known as DTA (AB-DPTA). The results showed normal levels of all elements, except zinc. The compositions of WT rubber were also compared with those of sewage sludge. The former contains lower concentrations of metals than does the sewage sludge, except zinc (STMC, 1996).

4.3 Impact of WT on Aquatic Ecosystems

A group of scientists in Canada conducted toxicity tests using leachate from three types of automobile tires, new tires, four-year-old used tires, and scrap tires that were part of a ten year old floating breakwater. The team performed acute static lethality tests of the leachate on rainbow trout (Salmo gairdneri), fathead minnows (Pimephates promelas), and a species of zooplankton (Daphnia magna).

The leachate produced by the ten-year-old scrap tires showed no toxicity to any of the test organisms. Leachate from new tires and the four-year-old tires were toxic to rainbow trout, although the other two test organisms remained unaffected. Further studies characterized the toxic substances as persistent and non-volatile (Day, et al., 1993).

The study results show that new tires may leach out some toxic chemicals, which supports the hypothesis concluded by the researchers from the State of Minnesota: the coating substances from new tires may be the main reason contributing to the toxicity of leachate. The concentrations of the toxic pollutants from the coating will persistently decrease with the leaching and the longer use of tires.

Additional states including Florida, Maryland, Virginia, New Jersey, New York, Washington and California, among others, have completed scrap-tire underwater breakwaters and fish habitat projects successfully over the past 32 years without adverse effects on terrestrial or aquatic environments being reported (SSMC, 1996). This provides additional evidence that scrap tires do not have hazardous behavior to cause severe impacts on the environment when properly used in highway construction.

4.4 Acute Oral Toxicity Test

Rubber products called "Sports-Turf™," a mixture of black rubber pieces with brownish fibers, manufactured from scrap tires by ATR, in Jacksonville, Florida were tested for oral toxicity (Breheny, 1995). The purpose of this test was to determine whether acute health hazards could be associated with ingestion of WT. When tested, an aqueous extract of WT did not induce any mortality in laboratory animals. Oral dosages of 15 g/kg, were used. Ten Sprague-Dawley rats (5 male, 5 female) were administered an oral dose of aqueous extract of WT 15 g/kg from March 17, 1995 to March 31, 1995. All animals appeared normal throughout the 14-day observation period. It was concluded that an aqueous extract of the test article was essentially non-toxic to laboratory animals following oral administration at 15 g/kg dose level (Breheny, 1995).

4.5 Potential Fire Hazards of Using WT Fill

There have been occasional reports of fires occurring in stockpiled scrap tires. For example, in 1983, stockpiled scrap tires burned continuously for nine months in Winchester, Virginia; in the mid-1980s, a pile with 1 million scrap tires caught fire in Everett, Washington; a stockpiled tire fire broke out during the fall of 1995 in Northern Michigan, and in 1990, a fire raged in stockpiled scrap tires in Hagersville, Ontario for 17 days. More recent reports were about the highway projects using WT chip fill in Washington and Colorado. Fire hazards have always been the main concern for discarded tire stockpiles. Unfortunately, potential burning can still occur in the WT chips placed as fill underground. Several reasons contribute to the spontaneous combustion of WT chips. Proper approaches in design and construction of WT fill are necessary to minimize this potential hazard.

According to recent investigations, the primary reason for WT chip burning was substantial heat accumulation, by exothermic reactions from oxidation of exposed steel wires from shredded tires. This exothermic reaction was accelerated by the existence of fine steel wire particles in tire chips, and the reaction rate increased with the raised temperature and lower pH environments. The chemical reaction involved can be expressed by (Humphery, [b] 1996):

$$4\,Fe + 3\,O_2 + 6\,H_2O \longrightarrow 4\,Fe(OH)_3 \quad \text{.............................} \quad (4-1)$$

In this chemical reaction, oxygen consumed in the oxidation of iron may come from the infiltration of surface air, or the air trapped in large void spaces of WT fill. This is identical to the metal oxidation exposed to open air. Because the WT fill is so thick and WT chips have an excellent heat-insulating property, these factors could expedite the heat build-up in the fill layer and raise the temperature very quickly. As this process continues, it may have been able to provide sufficient heat for another chemical reaction to be induced. This induced reaction is endothermic, called a pyrolytic process. As the pyrolysis proceeds, pyrolized WT chips heat up and chip morphology changes significantly. Pyrolization, or heating in anaerobic conditions, causes destructive distillation of WT rubbers and produces petroleum products, thus causing a roadbed to smolder. Based on the chemical analysis of WT chips made by Electrical Power Research Institute (EPRI), the component elements and their relative weight percentages are indicated in Table 4-1 (Crichlow, 1996). Using this ultimate analysis data, the chemical formula of WT rubber was derived as $C_{699}H_{716}O_{17}N_2S_4$. Thus, the pyrolytic process can be represented by the following reaction:

$$C_{699}H_{716}O_{17}N_2S_4 \xrightarrow{\text{HEAT}} 5H_2O + C_6H_8O + CO + CO_2 + N_2 + 4SO_2 + CH_4 + 347H_2 + 690C \quad \text{...} \quad (4-2)$$

The products from this endothermic reaction include (1) gas stream containing primarily hydrogen (H_2), fuel gas methane (CH_4), water vapor, carbon oxides, etc.; (2) tar and/or liquid petroleum products represented by C_6H_8O; and (3) a char consisting of almost pure carbon.

To stop WT stockpiles from accumulating enough heat to cause WT chips to burn several precautions should be taken. The most common design deficiency was that the WT chips were placed so thick that there was insufficient soil cover above the layer (26 - 50 ft thick embankment fill, and 70 ft backfill in the retaining wall). The qualitative hypothesis is that thick deposits of WT chips may react just like an underground heat reactor, where high energy rubber is so abundant and there is sufficient air available to cause exothermic oxidation.

Table 4-1 Ultimate Analysis of Shredded Tires (Crichlow, 1996)

Chemical Elements	Sample 1	Sample 2	EPRI*
Sulfur	1.5	1.52	1.23
Carbon	80.28	75.47	83.87
Hydrogen	7.56	6.82	7.09
Nitrogen	0.37	0.29	0.24
Oxygen	4.49	3.8	2.17
Moisture	N/A	4.23	0.62
Ash	5.81	7.87	4.78
Total	100.0	100.0	100.0
HHV** (Btu/lb)	15,879	14,230	16,250
* - Electric Power Research Institute			
** - High Heating Value			

There were two theories used to explain the causes of WT fill burning. One theory is the burning of WT rubber is the direct result of chemical oxidation. To measure the heat released from the oxidation of iron, theoretically, we can calculate the change of enthalpy through this chemical process. Based on the chemical reaction given in Equation 4-1, the standard heat of reaction ($\Delta\hat{H}_r^0$) can be calculated by using the following simulated chemical reaction (Hess's Law):

$$4\ Fe \div 3\ O_2 \longrightarrow 2\ Fe_2O_3 \quad \text{...} \quad (4 - 3)$$

where, the standard heat of formation ($\Delta\hat{H}_f^0$) for Fe_2O_3 is 822.2 kJ/gmole (Felder, et al., 1986), and zero for elements Fe and O_2. Therefore, the standard heat of reaction ($\Delta\hat{H}_r^0$) for (4 - 1) will be:

$$\frac{1}{2} \times 822.2 - 0 - 0 = 411.1 \text{ kJ/gmole} = 3170 \text{ Btu/lb.}$$

This implies that for every pound of iron that is oxidized, theoretically, the heat released would be equal to 3170 Btu.

The temperature increase of WT rubber in the fill results from the chemical oxidation from Equation 4-1. To analyze the effect of the chemical oxidation of iron on the temperature increase of WT rubber, the following assumptions were made (Humphery, [b] 1996):

- Tires contain 10% steel by weight
- In-place dry density of WT fill is 52 pcf (based on the Oregon landslide repair project)
- In-place water content of WT fill is 4%
- Mass heat capacity of steel is 0.11 Btu/lb°F
- Mass heat capacity of tire rubber is 0.48 Btu/lb°F
- Mass heat capacity of water is 1 Btu/lb°F

Using these assumptions, the volumetric heat capacity (C_v) of WT fill was estimated using the following calculation:

$$C_v = \frac{52}{100} x(10 \times 0.11 + 90 \times 0.48 + 4 \times 1) = 25.12 \ {}^{\text{Btu}}\!\!/_{\text{ft}^3\,{}^\circ\text{F}} \ .$$

If we further assume that all heat generated from the chemical oxidation of iron was available for a temperature increase of WT rubber, then the temperature increment (ΔT) of WT rubber can be calculated.

$$\Delta T = \frac{\Delta \hat{H}_r^0}{C_v} = \frac{3170}{25.12} = 126^0\text{F}.$$

This implies that for every pound of iron that is oxidized, it will potentially increase the temperature of 1 ft^3 WT fill by 126°F. Recalling that tire rubber begins to ignite around 600^0F, if a typical soil temperature were assumed to be 75^0F, and all the heat produced from the steel wire oxidation contributed to the combustion, calculation indicates that oxidation of about 4 lb (i.e., (600-75)/126) steel wire would cause 1 ft^3 of tire rubber to combust. If all the assumptions are holding true, auto-combustion of WT rubber in the fill would be possible, because the reaction heat of iron contained in 1 ft^3 of WT fill (> 4 lb according to the assumption) is sufficient to sustain the tire rubber burning in an equivalent volume of the WT fill. Combined with the effects of liquid petroleum products and fuel gases from pyrolysis process, burning of 1 ft^3 WT rubber may not need such amounts of metal oxidized because these pyrolytic products have a relatively lower burning point. This process may explain that for excessively thick WT chip fills, lack of proper screening of fine fill material, improper handling during placement, deficiency in construction design, particular ambient factors like pH, temperature, etc., the spontaneous combustion of WT chips occurs. All these factors help accelerate the oxidation and heat accumulation in the WT fill layer.

The WT fire in Washington, may have been the result of special circumstances. These conditions are summarized through the following 3 points.

1. The thickness of the WT chips buried beneath the roadbed was too high, plus additional oxygen was present because the thin soil cover did not decrease the void spaces enough to limit the oxygen.
2. The WT fill was located within a flood zone. It is possible that massive floods the previous year saturated the WT fill, and that the remaining water accelerated the oxidation process (rusting) of exposed steel in the scrap tires creating enough heat to ignite the WT chips.
3. The insulatory properties of tire rubber helped sustain the heat and accelerate the heat build-up. Another possible factor attributed to the combustion was the involvement of microbes in the oxidation of steel wires that may have triggered the low pH environment in the WT fill layer. Low pH conditions and elevated temperatures help expedite the oxidation process of steel wires, contributing to substantial heat build-up.

A second combustion theory involves the burning of liquid petroleum products and fuel gases derived from the pyrolytic process accompanying the chemical oxidation. From the pyrolytic reaction presented in equation 4-2, most of the products formed are either liquid oils or fuel gases. A large percentage of solid tire rubber changed into gaseous products. The effect of this change would cause substantial volume reduction of the WT fill layer. Field measurements on the burning road in Ilwaco, Washington, indicated that as much as one foot of settlement had occurred (Humphery, [b] 1996), in the highway project located in Garfield County, Washington, as many as 8 ft of roadway surface settlement was reported (Cosentino, [a] 1996). This large settlement resulted in the formation of cracks in the pavement surface, which served as channels for air infiltration into the fill to cause petroleum oils and fuel gases to combust under the conditions of sufficient air and temperature.

4.6 Summary of Environmental Concerns

WT highway fills do not show severe threats to human health and the environment. Adverse effects from their leaching can be prevented by proper handling and placement in the highway. The preferred approach is to place shredded WT in unsaturated zones and construct WT fill as an encapsulated layer. The potential fire hazards of WT chip fill can be controlled by; 1) limiting the amount of steel wire exposed at the cut edges of the WT chips, 2) proper screening of the fill materials to eliminate the liquid petroleum contaminants, and 3) placing sufficient low permeability cover soil to minimize contact of WT chips with oxygen and decrease available void space that can trap oxygen. Larger diameter WT shreds are advisable due to their decreased surface areas and fewer cutting surfaces, thus reducing the amount of exposed steel that can be oxidized.

5. ECONOMIC CONSIDERATIONS

Before any alternative road-building material is introduced, a cost-benefit analysis must be performed to ensure that the anticipated benefits exceed the economic costs. The economics related to construction materials come mainly from the costs of extracting, processing, and hauling these material to the site (Sherwood, 1995). The potential costs and benefits of using WT chips in highway construction must be understood. Michael Blumenthal, executive director of the Washington, D.C.-based Scrap Tire Management Council, when asked about the set backs from the scrap tire fires stated that "the negative response gained from the publicity of these projects is going to adversely affect five years of positive experience with the tire fill applications" (White, 1996).

5.1 The Effects of Legislation Status

In the United States, only Alaska, Delaware, and New Mexico lack scrap tire regulations. Of the remaining 47 states, at least 33 have a mechanism for tire abatement (Rosenberg, 1996). In Florida, whole scrap tires may not be disposed of in a landfill. Scrap tires that have been cut into sufficiently small parts may be disposed of or used as initial cover at a permitted landfill (FAC, 1995). To meet these requirements, scrap tires have to be processed prior to disposal in landfills. The increased cost for scrap tire disposal is considered to be a trade-off for decreasing landfill space, thus extending the life of landfill cells as well as benefiting the environment.

At present, landfills in Florida require that 70 percent of shredded tire chips be less than 4 square inches, and 100 percent shredded tire pieces be no larger than 32 square inch or less when using shredded WT as the initial cover. Even to be disposed of in Florida landfills, WT must be cut into at least eight substantially equal pieces (FAC, 1995). To meet these sizing requirements, Florida's processing cost is approximately $38/ton (Giberhart, 1996). In Wisconsin, the cost of tire shredding was reported to range from $30 to $65 per ton of scrap tires (Bosscher, et al., 1994). Both sources reveal costs higher than the average shredding cost of $25/ton nationwide (Bloomquist, 1993).

5.2 The Effects of Applications

From the end user's viewpoint, the material cost is largely dependent upon the specifications to be used in various applications. Generally, classification is performed according to the end products of tire processing and rubber recycling. The processing cost relates not only to the size reduction requirements, but also to the processes involved and the capital cost for these processing equipment. In the tire processing and rubber recycling industry, mechanical and cryogenic processes are commonly utilized, additionally, devulcanization, and thermal-friction-screw-system are involved. For example, cryogenic processes utilize liquid nitrogen to freeze rubber prior to size reduction. The cold rubber becomes brittle and is readily shattered into fine particles in a hammermill. This process is combined with mechanical processes for producing crumb rubber. Particle size distribution ranges from 10 to 60 mesh, with the most common products being 10 to 50 mesh. The major operating costs for cryogenic process are associated with the nitrogen that can cost between $0.12 and $0.18 per kilogram of product depending on feedstock sizing, efficiency, nitrogen cost, and product yield. Energy, manpower, and plant-related overhead generally add $0.15 to $0.26 per kilogram of product with the higher cost incurred in whole tire shredding operation. Total production costs, therefore, range from $0.27 to $0.44 per kilogram, or about $1.89 to $3.08 per passenger tire equivalent (1st American Scientific Corp., 1996). Assuming each tire weighs about 25 lb, per ton costs would range from $150 to $250, making the processing costs much higher than those for TDF, highway applications, and landfilling. Therefore, scrap tire production costs can make their use as a fill questionable.

Devulcanization is used to sever the sulfur bonds in the molecular structure of scrap tire rubber. Scrap rubber is converted from a thermoset elastic state to a plastic state, thus providing a fresh stock for new tire production. This makes so-called "true rubber recycling" possible. The operation may be economically feasible, but the capital cost for devulcanization equipment could be substantially high. According to the officials at ATR, the devulcanization equipment may require a direct investment of $500,000. This investment would be sufficient for starting one or two processing facilities for shredding scrap tires into relatively small pieces. For example, the portable-type tire shredder offered by Mitts & Merill, costs between $400,000 and $425,000/unit, and can produce 8-10 ton/hr of WT shreds per pass; while their stationary type shredder, costing between $250,000 and $275,000/unit, has the production capacity of 5-7 ton/hr of WT chips 2 in. minus, or 2.5-3 ton/hr of WT chips 1 in. minus (Kreith, 1994). Based on processing costs, producing CRM would be the most expensive material, followed by recovered rubber products such as play area cover, sports turf, and safety devices, then TDF; and finally, WT chips for highway fill and for landfilling.

5.3 Effects of Hauling Cost

Using shredded WT chips in highway construction involves higher than expected hauling costs because the shredding facilities are invariably far from the construction site. For this reason, they may constitute the major portion of the procurement cost of shredded scrap tires. Shredded tires may be obtained free from the local county landfills to help reduce costs. Scrap tire processors would rather give them away than pay tipping fees for their disposal in landfills. Generally, the tipping fees for scrap tires range between $100 and $200 per ton, or $1.00 per tire for unshredded tires, and between $1.00 and $10.00 per ton for shredded tires (Town of Colonie, 1996).

A landslide repair in Oregon required 5,800 tons of shredded WT fill. Haulers were paid \$30 per ton delivered the site. The hauling mileage ranged from 150 to 200 miles (Read, 1992). The tipping fees in Oregon average \$5/ton for WT when added to the \$25/ton for shredding the tires, it can be concluded that the hauling costs for shredded WT were equal to the material handling cost. Although haulers were paid \$30 per ton delivered, the incurred material cost was only \$10 per ton, or \$7.02 yd^3 after the final in-place density was measured. The balance of \$20 per ton was paid by state reimbursement.

In Garfield County, Washington, a project used 400,000 cubic yard of WT's to fill a 50 ft deep ravine. The fill was shipped from the source, about 115 miles away from the project site. The cost, including shredding, transportation to the site, and a subsidy from the Washington State Department of Ecology, was about \$0.50 per tire, or approximately \$50 per ton (King, 1995). If the average shredding cost of \$25 per ton is assumed, the transportation expense constituted 50 percent of the total cost.

In another instance, the WT chips 1 inch minus used as fill in a roadway project in Maine were delivered to the site from four different suppliers, at costs ranging between \$12 and \$25/yd^3 or between \$30 and \$63 per ton, while in a similar situation, WT chips could be obtained at \$0.40/yd^3 or \$1.00 per ton in Vermont, and \$1.50/yd^3 or \$4.00 per ton in New Hampshire (Manion, 1992).

5.4 In-place Cost

The in-place cost includes the expense of machinery and manpower needed for the installation. For example, a WT fill highway embankment in Maine used two D-6 Dozers for WT chip spreading and compaction at a cost of \$110/hr per unit, including manpower and machinery. Using both dozers, about 225 cubic yards of WT fill could be compacted per hour with five compaction passes. This project required approximately three 30-ton truckloads of tire fill materials (Note: There are about 40 scrap tires/yd^3, and one ton of scrap tires is equivalent to 2.5 cubic yards), and the installation costs were about $1.00/yd^3. If the cost of geotextiles used in this project is added (estimated at $2.00 per square yard), and a 4 feet layer of chip fill was placed, the in-place would be $1.50/yd^3 (or $3.75/ton). In Vermont, the in-place cost for a highway tire fill project was reported at $1.65/ yd^3 (or $4.20/ton) (Manion, 1992).

Another project that reflects cost data is a retaining wall on Division Street in Mankato, Minnesota. In this project, rubber blocks made from shredded tires were used to build a retaining wall with WT chips as backfill. The cost of the wall was about $25 per square foot of face, which fell with in the range of costs reported (between $20 to $30 per square foot of face) for cast-in-place walls (Arlig, 1995). Arlig suggests that the costs of WT retaining walls would decrease when contractors gain experience with these materials.

5.5 Effects of Incentive Programs

There are various incentive programs adopted to rid the state of their waste tire overload. In Wisconsin, state-sponsored financial incentives play an important role in utilities' decision to choose scrap tires for generating power. Grants from the Wisconsin Department of Natural Resources paid for temporary TDF handling facilities and flue gas testing during the initial test firing. Similar grants were given to many power utilities to encourage use of TDF. Wisconsin has offered $20 per ton for scrap tires used in boilers for energy recovery since 1990. Again in 1995, Wisconsin adopted a program that offers individual or businesses that process scrap tires an additional $20 per ton, meaning that a utility that both processes tires and uses them in its boilers can receive a reimbursement of $40 per ton.

The incentive program offered through the Illinois Department of Commerce and Community Affairs is among the most aggressive in the country. They offer grants and loans to encourage the use of TDF, including funding to help vendors of TDF establish their businesses. Utilities and others have relied on this money to conduct test burns and to purchase equipment for tire-burning plants (Lamarre, 1995).

In Texas, a new state law pays cement producers 40 cents for each tire burned. The Texas Natural Resource Conservation Commission has millions of dollars in grant money reserved for facilities that want to use TDF (Bryce, 1996).

In summary there are numerous incentive programs available to combust tire for energy, thus reducing the available number for highway applications.

Tire recyclers are also beneficiaries of grants or loans. For example, ATR in Jacksonville, Florida, has obtained grants from the state-sponsored incentive program to upgrade its equipment or reinvest its processing facilities. Its proposed devulcanization equipment will be fully paid for with the grants it received. ATR is also reimbursed with a scrap tire disposal fee of $1.50 for each passenger tire, and $5.00 for each truck tire processed.

Public attitudes on the use of WT as fill in highway construction are important. In some cases, the naturally occurring materials used in road construction are relatively cheap and readily available, and sometimes there is just too much in stock. In addition, the fill material cost forms only a small portion of the total cost of the road construction. These factors cause contractors to "play it safe", even if naturally-occurring materials cost more. That is why it is necessary for highway authorities to set clear standards and specifications to provide guidelines on the use of scrap tires. Recognition by the authorities gives a permissive attitude for the use of shredded WT in highway construction, and allows freedom for contractors to make choices. By combining new incentives with those applied to TDF users, public attitudes can be changed. The beneficial uses of this material would help stop the belief that highway fill application could be another form of landfill disposal. Unless the attitude is shifted to favor this application, contractors would rather spend needless expenditure than take the risk facing criticisms that occur if a potential costly failure should arise.

5.6 Summary

The costs of WT for use as highway fill is relatively high, indicating that it may not be the best approach for using this waste product. The only real benefit to its use as a fill would be the potential savings of landfill space, however, the many TDF incentive programs make this benefit unlikely.

6. BEST MANAGEMENT PRACTICES FOR SCRAP TIRES

Scrap tires are valuable resources. They should be managed in the same way as natural resources. Current research suggests that using scrap tires for fill in Florida highway construction would be an expensive management practice. Tires pose minimal environmental concerns, but their poor elastic behavior requires special consideration for use as a fill. The suggested BMP for Florida would be continue using the tires to create energy as TDF.

Field projects conducted by highway departments in Maine, Colorado and Washington detail the procedures necessary for BMP use of WT chips if they were to become attractive highway fill materials. The most critical concern is avoiding combustion of the scrap tire fill. This can done by limiting the thickness, the amount of exposed steel, and the oily contaminants in this fill.

Environmental impacts need to be verified in both laboratory testing and field demonstration. EPA standards can be followed in characterizing the leaching behaviors of shredded WT chips. Models may be established on the shredded WT leaching behavior that leachate concentrations decrease with the leaching time and the age of tires put into use, as compared to measurements from the field demonstration project. The BMP model suggested may be represented by the conventional formula

$\frac{dC}{dt} = -kt$, where C is the leachate concentration of specific contaminant, and t is leaching time; and k is the empirical coefficient that is dependent on the age of waste tires and the contaminant of concern.

7. CONCLUSIONS

Shredded WT chips exhibit engineering properties that are favorable to highway construction. Their lightweight and free draining behavior can be advantageous for foundations on weak soils. The wide variety of applications in highway construction will could help solve the scrap tires disposal problem, although their costs are most likely prohibitive.

The following conclusions were developed from the BMP:

1. Shearing-type shredders for processing WT yield a cleaner cut and fewer protruding metal wires. Impact type or hammermill shredders operate at higher speeds (1200 to 1800 rpm versus 10 to 30 rpm), however, they tend to tear the tires and produce a nonuniform material with the steel beads extending outward. The more uniform WT products produced from the shearing process will facilitate handling during hauling and field construction. The potential fire risk from oxidation of exposed metal parts is minimized when shearing-type shredders are used.
2. Two factors should be considered for proper sizing of WT chips: processing costs and acceptable highway construction size. Sizing chips 1 inch or less is not economical, while chips larger than 24 inches cause engineering behavioral problems. WT chips ranging from 4 inches to 12 inches have been shown to be practical both in terms of cost and performance. In specifying WT chip size, selection of the engineering sieve that will allow 80% of WT chips to pass through as nominal or representative size of WT chips was recommended by Manion, Nickels, and Humphrey (Manion, 1992), (Nickels et al., 1995), (Humphrey, 1996a).
3. Shredded tire chips can be categorized as lightweight coarse materials. They have in-situ densities ranging from 20 to 35 pcf (3.1 to 5.5 kN/m^3). These ranges depend upon top size and gradation. Sieves can be used to classify the nominal size of WT chips.

4. The bulk unit weight of WT chips varies as a function of size and shape. Due to the high compressibility of WT chips, loading, hauling, and placement measurement by weight is deemed to be practical. Compaction control needs to be monitored using predetermined WT weights and known fill volumes instead of relative compaction.
5. WT chips exhibit nonlinear cohesionless stress-strain behavior and are highly compressible compared to conventional granular soil fill. During field placement, initial settlement can be expected to be substantial and not time-dependent. The resilient modulus of WT chips is stress-dependent and typically so low that it may impede their potential pavement layer applications.
6. WT chips exhibit excellent frictional behavior making it possible to reinforce soil with WT chips to enhance slope stabilization.
7. WT used as highway fill have not shown any severe threat to human health or the environment. Adverse effects of their leachate can be prevented by proper handling and placement. The preferred approach is to place WT chips in unsaturated zones within an encapsulated layer.
8. The potential fire hazards of the WT chip fill can be controlled by screening the WT products to be used as fill, and placing sufficient low permeability cover soil to minimize contact with oxygen. In addition, relatively large WT chips are advisable for such use because of the decreased surface areas and fewer cutting surfaces exposed, thus reducing the amount of steel that can be oxidized. It is also required that WT fill layers be constructed where extreme pH environments or fluctuating pH conditions are nonexistent.

8. PRELIMINARY SPECIFICATIONS OF SHREDDED SCRAP TIRES AS FILL IN FDOT HIGHWAY APPLICATION

8.1 Description

Shredded scrap tire fill can be any chipped rubber tire pieces processed from any type of scrap tires: passenger and/or truck tires; fiber glass-belted and/or steel-belted tires. Shearing-type shredding equipment must be used.

Processed scrap tire fill must be free from oils, grease or any contaminants that could create hazardous leachate that could threaten the environment.

8.2 Gradation

The fill shall consist of 100 percent chipped rubber tire pieces meeting the following requirements:

1. The largest allowable piece is 1/4-circle in shape or 24" in length whichever is the lesser dimension.
2. 100 percent of the material (by weight) must pass an 8" screen.
3. All pieces shall have at least one sidewall severed from the face of the tire.
4. All metal fragments shall be firmly attached and 98 percent embedded in the tire sections from which they were cut. Ends of metal belts and beads are expected to be exposed only in the cut faces of the WT chips.
5. The lightweight fill material supplied shall weigh less than 700 pounds per cubic yard (equivalent to 26 pcf), by truck measures.
6. Unsuitable material delivered to the project shall be rejected in truckload quantities and removed from the site at the cost to the supplier.

8.3 Fill Construction

Construction of shredded rubber tire fill shall meet the following requirements:

1. The shredded WT fill shall be deposited through end dumping by trucks. Backhoes or bulldozers are appropriate for spreading WT fill material evenly.
2. Construction of shredded WT fill should employ track-mounted vehicles or equipment to facilitate travel pass over the fill.
3. The WT fill shall be placed in layers not to exceed three (3) feet thick.
4. Shredded WT fill can be blended with sand or other granular soils up to 40 percent by volume of the embankment fill portion. In using WT chip soil mixtures, fill shall be constructed by placing alternate layers of shredded WT chips and soil, and mixing and blending during compaction. Chip-soil mixture should be manipulated sufficiently to minimize voids within the mixtures.
5. The top of the WT fill shall be constructed with a top elevation of 12 inches above the finished elevation to allow for shrinkage. The sides of the lightweight fill shall be overbuilt to allow for final trimming. The side slopes shall be smooth and compacted.
6. After final trimming, the WT fill shall be covered with construction geotextile for soil stabilization. A barrier layer consisting of 3"-4" thick non-chip soil should be placed on top of the shredded WT chips to prevent punctures or tears in geotextile fabrics during installation.
7. Shredded WT fill shall be placed within the embankment boundaries as follows:
    a. Bottom - minimum 2' above the high-water table.
    b. Side - minimum 4' inside the side slopes.
    c. Top - minimum 5' soil embankment cap layer.
8. Shredded WT chips should not be used in areas of pH values less than 3.5, or more than 8.0.
9. Shredded WT fill shall not be placed in areas subjected to long durations of flooding.

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APPENDIX A

Summary of WT Highway Projects

Summary of Highway Projects Using WT Fill

(1) No.	(2) State/Year	(3) Project Name	(4) Quantity Used (yd³/tons)	(5) Shred Type	(6) Shred Size (in)	(7) Fill Depth (ft)	(8) Ground Water Table	(9) Mixed With Soil	(10) Spreading & Mixing	(11) Compactor Type & Method	(12) Lift Thickness (ft)
1	VA/1993	Rt. 646 connection	55000/17000	steel/glass belted	max. 10	20	2' above GWT	50/50 by volume	bulldozer & grader w/scarifier	sheepsfoot roller	2
2	ME/1992	Gravel road with shred insulation layer	650/200*	steel/glass belted	2	0.5-1.0	above GWT	no soil mix	bulldozer	smooth-drum roller	as fill depth with 1/2" grade
3	WI/1991	Test** embankment	N/A	steel/glass belted	max. 4x18 common: 2x3	6	above GWT	pure shred; shreds+sand 50/50 by volume; layered with soil by volume ratio 50/50	backhoe, better than loader or grader	12T sheepsfoot roller with vibratory capability 26T	1
4	MN/1993	Field test	25 truckloads	steel/glass belted	avg. 12x12	6	above GWT	no soil mix	loader	27T caterpillar bulldozer	3
5	MN/1989	Benton	1700/520*	N/A	max. 12	3	0.5' above GWT	no soil mix	caterpillar loader	caterpillar loader	2
6	MN/1991	Scot watermain backfill	N/A	N/A	max. 3	6	above GWT	no soil mix	caterpillar bulldozer	caterpillar bulldozer	3
7	MN/1991	Athens T194	N/A	N/A	N/A	3	above GWT	no soil mix	caterpillar loader	caterpillar loader	3
8	MN/1991	Prior Lake	9600/2900*	N/A	4-6	3	above GWT	no soil mix	loader	bulldozer	3
9	MN/1991	Eden Prairie	4000/1200*	N/A	L:12-24 W:6-8	9	above GWT	no soil mix	loader	caterpillar bulldozer	2-3
10	MN/1991	Esker Trail	1000/300*	N/A	L:12-24 W:6-8	3	above GWT	no soil mix	loader	low ground pressure buildozer	3
11	MN/1989	Centerville Road	2500/750*	N/A	max. 4	5	above GWT	no soil mix	loader	bulldozer	5
12	MN/1991	Convention ctr parking ramp	2500/750*	N/A	L:6-12	3	above GWT	no soil mix	loader	bulldozer	3
13	MN/1992	Pine County	3000/9000	N/A	max. 12	1-15	2' above GWT	no soil mix	bulldozer	bulldozer	1
14	MN/1990	Lake County	3900/1200*	N/A	L:12-1/4 of tires	4	1-2' above GWT	no soil mix	bulldozer	bulldozer	4
15	WA/1995	Ilwaco, SR100	13000/4000*	steel belted	L:4-6 W:2	26	above GWT	no soil mix	caterpillar bulldozer backhoe for side slope	caterpillar bulldozer 7000lb, min.	0.5-1
16	WA/1994	Garfield Co. embankment	16500/12000	steel belted	max. 12	30	above GWT	no soil mix	caterpillar bulldozer	caterpillar bulldozer	1-1.5
17	OR/1990	Slide Repair, Roseburg	8260/5800	steel belted	max. 24	12-12.5	12" above drainage blank	no soil mix	D-8 bulldozer	D-8 bulldozer	3
18	ME/1993	Yarmouth Low Volume Test Road	3200/1000*	mixed	max. 3 max. 12	2	above GWT	no soil mix	track-mounted bulldozer	smooth-drum vibratory roller more effective	1-2

Summary of Highway Projects Using WT Fill

(13) Minimum Passes	(14) Geotex-tiles	(15) Top Cover Soil	(16) Side Slope Cover Soil	(17) Monitoring Program	(18) Existing Problems	(19) Density (pcf)	(20) Young's Modulus (psi)	(21) Poisson's Ratio
3	N/A	5' soil	4' soil	groundwater	settlement twice that of conventional section, vertical expansion, higher cost (37%) than conventional fill	avg. loose density 25.0; mixing soil 50/50 by volume 71.3		
6 with 0.5-1" compacted for 1' thick layer	Y	1'-2'	min. 2'	thermal behavior, road surface support & groundwater	handling in placement of shreds, shreds spill beyond the desired offset	compaction induced by 6.7%.		
5	N	max. 3' soil	N/A	leachate analysis	little plastic deformation upon compaction, density 25-35pcf after compaction, pothole developed under heavy truck traffic, only first pass inducing compaction	pure chip range, 19.3-35.7 ; chip-soil mix, 75.7 compacted at different chip thickness & chip sizes.	152.8-256.9	0.2
<22 effective 15	N	1.5' sand	N/A	settlement	damage to equipment settlement plate during construction	bulk unit weight, 14.5 uncompacted; avg compacted, 22.0	112.5 model test for chip size <2 in	0.45 one-dimensional compression testing
N/A	Y	1' granular materials	N/A	settlement	moderate longi-tudinal cracking, rutting			
N/A	Y	2' soil	N/A	No	N/A			
N/A	Y	1.5' sand	N/A	No	N/A			
visual observation	Y	2.5' sand & gravel	N/A	settlement & deflection	tire shreds very compressible, relatively low E value	material supplied less than 22.2		
<10 40-45 pcf	Y	4' soil	N/A	settlement of peat & tire fill	N/A			
N/A	Y	2' soil granular	N/A	settlement of peat and tire shred fill	N/A			
N/A	Y	3' granular	N/A	No	N/A			
settling about 30% of total thickness	Y	0.5' sand	N/A	No	N/A			
N/A	Y	5' granular	3' granular	deflection	N/A			
N/A	Y	1.5' granular	N/A	No	N/A			
3	Y	4' granular	2' topsoil	settlement, air & water quality, temperature	pavement crack settlement equivalent to 2.3% compression of tire shreds & exothermic reactions causing combustion			
by judging	N	4'-7' gravel	1.5' topsoil	N/A	settlement & exothermic reactions causing combustion open flames			
3 full coverage passes	Y	3' common borrow	3'	settlement, deflection & computed density	short-term compression,13.4% deflection twice as the conventional type, vibration	loose: 30; computed as compacted, 45 under loading & pavement, 52		
<10	Y	5"-29" subbase: 25"	N/A	leachate, static & dynamic pavement deflection, groundwater	N/A	38-43 loose 25	200 assumed value in FE analysis	0.32 assumed value in FE analysis

WT Fill Highway Project Descriptions:

1. A comparative performance of conventional and shredded tire embankment was conducted. The results showed that the settlement of a shredded tire embankment exceeds that of a soil embankment. Vertical expansion was also observed.

2. Tire shreds were used as an insulation layer to limit frost penetration beneath a gravel road. The road is 750 ft long, consisting of five sections with different chip thickness ranging from 6-12" and granular soil caps ranging from 6-12". Results show that a 6" chip layer can reduce frost penetration by up to 25 percent. The gravel cover should be 12-18" thick to provide a stable riding surface.

3. Test embankment constructed with 6 sections of 20 ft long each. Different chip fill thickness and soil cover depth were installed to evaluate their performances. Pure chip fill and chip-soil mixture fill performances were also compared.

4. An aggregate surface road with tire shreds subgrade was constructed. A 700 ft long road was constructed with 4 sections consisting of tire shred subgrade. The objective was to determine the settlement of tire shred subgrade as a function of the cover thickness and compaction effort.

5. Reconstruction of a 250 ft section of a rural road embankment was performed. This embankment failed due to overloading the underlying 12 ft peat layer. Solution required replacement of heavier earthen fill with lightweight shredded tires.

6. Tire shreds were used as lightweight backfill over an existing watermain at a swamp deposit.

7. A road that required additional fill due to the settlement of the peat subgrade. Lightweight shredded tire fill was used to replace normal sand fill. The objective was minimize settlement of the underlying peat by using WT fill.

8. The roadway site was characterized by 30 ft thick swamp deposits. The objective of using WT fill was to reduce settlement of peat and maintain embankment stability.

9. The embankment was placed over about 40 ft of soft organic soil. The embankment failed due to the use of soil fill. Replacement of soil with WT fill was to reduce the settlement of the embankment.

10. The subsoil of this forest road construction, consisted of about 5 ft thick swamp deposits. It was concluded that total deflection of the embankment constructed on weak subsoil with WT subgrade fill was about 50 % less than that of an embankment constructed with granular fill.

11. This site had deep deposits of swamp soils. WT fill was used to replace initial fill. The objective was to reduce settlement of the road.

12. This project used tire shreds as a substitute for heavier material to reduce the weight on the parking ramp. The reduction in weight allowed the construction of a park above the ramp.

13. This project used tire shreds to prevent the reoccurrence of a deep-seated rotational failure in a plastic silty loam underneath a ramp on I-35 in this city.

14. This was a reconstructed gravel road section, located at a bridge approach. It experienced excessive settlement because it was originally built over peat soils.

Tire shreds were used as fill to stabilize the roadway. No noticeable settlement on this segment has been reported since reconstruction.

15. Tire shreds were used to fill a gap, caused by a landslide in SR100 loop road. The gap was 140 ft long measured along the centerline and 25 ft deep. The tire shreds were placed directly on a rock drain. The side slopes of WT fill embankment were 1.75H:1V.

16. This is a gravel-surfaced county road. Tire shreds were used as fill in embankment construction. The embankment was constructed across the ravine. A 6 ft diameter corrugated metal pipe was used to carry an intermittent creek beneath the embankment. The side slopes of WT fill embankment were 1.5H:1V, with a crest 32 ft wide. The base width of the embankment was 192 ft.

17. This project was to show the effectiveness of WT fill in stabilizing landslide or soft soil problems; to determine construction problems associated with WT fill highway embankment.

18. This field trial is to determine the minimum thickness of the cover soil above the WT fill, and to study the effects on water quality of shredded tire chips placed above GWT.

APPENDIX B

Case Histories WT Highway Projects

Case Studies

To better understand how shredded WT were employed in highway projects, the following projects were chosen as representatives of how WT chips have been incorporated in highway construction to date. The case studies are analyzed in terms of material properties, construction procedures, and quality control as well as engineering performances. Some problems encountered in the application of WT were also examined.

(1) Wisconsin - Highway Embankment In Madison

The University of Wisconsin-Madison, in cooperation with the WDOT, has conducted a limited field test to determine the feasibility of incorporating shredded tires in highway embankments. In this study, a 16 ft (4.9 m) wide and 6 ft (1.8 m) high test embankment was constructed with ten different sections, each 20 ft (6.1 m) long. Locally available WT chips and soils were used in different combinations in the test embankment, varied from pure WT chips, chips mixing with soil, and WT chips layered with soils. There were also varied embankment configurations to determine the optimum slope. Geotextiles were placed on all sides of the WT chips to serve as a separator between embankment fill and surrounding materials. The embankment was built parallel to the access road of a sanitary landfill and exposed to heavy incoming truck traffic. The roadway performances could be monitored on long-term basis.

The fill materials used were from the local tire shredding facilities and consisted of a mixed type of waste tires (steel-belted and glass-belted). The sizes of particles varied between smaller size 2"x3" and maximum size 4"x20". The WT chips were either mixed with soils up to 50 percent by volume, or placed as pure chip layers in different test sections. The thickness of cover soil over the fill layer varied to evaluate the effects of different cover soil depth on the performances. In addition, the possibilities of layered WT chip fill construction were also evaluated to determine the best embankment configuration.

The field observations during construction included:

1. The handling and placement of tire chips were not a problem. A backhoe was found appropriate for spreading the chips evenly.
2. Neither vibratory nor static compaction significantly induced compaction in the tire chips. Non-vibratory compaction was found more appropriate.
3. The compacted field density varied from 20 pcf (3.1 kN/m^3) to 35 pcf (5.5 kN/m^3), depending on the layer depth and particle size of the tire chips. Higher compacted density can be obtained from smaller chip particles; and the chip-soil mixture can reach the compacted density of 70 pcf (11 kN/m^3).

A two-year monitoring and evaluations of the embankment performance reveal that:

1. After an initial adjustment period (approximately 60 days) for settlement, the overall road performance was similar to most gravel roads.
2. The embankment sections with 3 ft (91 cm) soil cap performed much better than those with a 1 ft (30 cm) of soil cap.
3. The WT chip/soil mixture performed similar to the pure chips with a thicker soil cap. The presence of a thick soil cap reportedly helps reduce plastic deformation; comparatively, the layered section was not easily compacted and performed the worst.

The design and construction specifications (Edil, et al., 1992) adopted in this test project can be summarized as follows:

1. The quantity of tire chips is better measured based on the weight, not volume.
2. Tire chip size is not a critical specification item. Although construction operations may be eased by specifying tire chips of 3" minus, the increased cost should be taken into account in field construction. Compression performance of large and small WT chips is believed to be comparable.
3. Compaction control should not be based on final unit weight, instead, an optimum number of coverage passes should be obtained based on a test section in the field. Vibratory compaction is not recommended because of the pressure-dampen behavior of WT chips.
4. Tracked equipment should always be used for any machinery that travels over the shredded tire fill to avoid any damage of rubber-tired vehicles caused by extruded wires from the WT chips. Backhoes or bulldozers perform well in spreading chips during construction.
5. The compacted unit weight of pure WT chip fills typically ranges between 19 and 35 pcf for the particle sizes of chips used in this project. Compaction and chip size have an influence on this value. The specific gravity of WT chips ranges from 1.13 to 1.36 (average value of 1.22) depending on the metal content. These values along with the specific gravity of other soils can be used to determine the unit weight of soil-chip mixtures.
6. The governing parameter in designing WT chip fill is the compressibility. A minimum soil cover layer of 3 ft overlying WT chips should be considered. Geotextiles are used to separate the cover soil from the porous chip fill to prevent migration of the soil into the chip matrix that could cause localized depressions.
7. An initial period of differential settlement in the fill should be accounted for in the WT chip fill design. Final surfacing should be constructed after this adjustment period.
8. Pavement structural design can be achieved by use of multi-layer elastic theory using appropriate resilient moduli for WT chip samples as determined in the

laboratory. The resilient modulus test cannot be run on pure tire chips, but can be estimated from the repetitive constrained modulus test.

9. Specification for repetitive constrained modulus tests on WT chips of 3-in minus should include:
   a. minimum of 6-in diameter mold
   b. standard Proctor compactive effort during sample compaction
   c. a seating stress of 2 psi
   d. repetitive vertical stress of 18 psi
   e. cyclic loading frequency of about 0.5 Hz
   f. repeat cyclic load until load-deformation curves converge
   g. computation of cyclic strain (based on specimen length at seating stress) determined from last cycle of load
   h. computation of repetitive constrained modulus as the ratio of cyclic stress (18 psi) to cyclic strain.
10. Sand or clay can be used in WT chip mixes although mixing of clay and WT chips in the field may prove difficult. Sand mixtures exhibit higher moduli than clay mixtures at the same soil/chip ratio.

(2) Oregon - Slide Correction Project

Based on the experience of Minnesota DOT in the use of WT as lightweight fill in embankments on soft foundation soil, the Oregon DOT also used WT chips in a landslide area on Highway U.S. 42. The slide occurred in a 15 ft (4.6 m) high embankment, with a slide block extending 150 ft (46 m) beyond the toe of the embankment to a small creek running parallel to the highway.

WT chips from four suppliers were used in this landsliding repair project. An estimated 580,000 shredded scrap tires were used to replace the existing fill to reduce the weight of the embankment. A drainage blanket consisting of 1 ft (30 cm) of free-draining rock between two layers of geotextile was deposited beneath the

WT embankment to prevent the groundwater table from rising into the embankment. Three 30 ft (9.0 m) deep French drains were installed beneath the blanket to enhance the subsurface drainage. The drainage blanket was required to prevent submergence of the WT into water.

WT chips were spread in 2 - 3 ft (60 - 90 cm) lifts and each lift was compacted with no less than three passes in each direction of a D8 dozer, achieving in-place density of 50 pcf (7.9 kN/m^3), compared to the reported density range of loose chips in the haulers varied from 24 pcf to 33 pcf (3.8 kN/m^3 to 5.2 kN/m^3), depending on the hauling distance and WT chip size. Post-construction density, under 3 ft (91 cm) of soil, 2 ft (61 cm) of aggregate base, and 6 inch (15 cm) of asphalt, and after three months under average traffic, was 52 pcf (8.2 kN/m^3) (Read, 1991).

To compensate for shrinkage of the WT chip fill that was expected to occur during the following construction, the WT fill was constructed to an elevation about 1 ft (30 cm) higher than the design height to offset a 10 percent anticipated compression (based on the settlement data of a test embankment in Minnesota). It was found that the thickest portion of the WT fill 12.5 ft (about 3.8 m) compressed 13.4% (20 in or 51 cm) during construction. The total compression consisted of:

1. 80% occurred during placement of soil cap;
2. 10% occurred during placement of aggregate base; and
3. 10% occurred three month traffic loading after placement of 6" asphalt concrete.

Four months after completion of the stage 1 soil cap and aggregate base construction, a Falling Weight Deflectometer (FWD) test was conducted to measure the pavement deflection. The average deflection of the pavement over the WT chip fill was approximately 0.020 inch (Read, 1991), which is twice as much as a typical deflection normally measured for a similar asphalt-and-aggregate base pavement constructed over a conventional soil subgrade. Another observation was a perceptible vibration of the WT embankment caused by heavy truck traffic. During stage 2 construction, while traffic was carried by the temporary surfacing on the south half of the embankment, vibrations, similar to what one would feel standing in the middle of a long-span bridge, occurred during passage of a loaded log truck. However, vibration was noticeably reduced following construction of the other half of the embankment.

(3) Colorado - Retaining Wall in Glenwood Canyon

A 70 ft (21 m) high retaining wall was constructed with WT as backfill in 1994 and completed the following year. The wall geometry included seven 10 ft (3 m) tiers, which were constructed with rubber wall blocks produced by Multi Block, Inc. The front face of the wall was made of 2 ft x 4 ft x 16 in (60 cm x 120 cm x 40 cm) blocks formed from shredded tire rubber mixed with latex. Approximately 80,000 waste tires were used in the wall blocks. The WT chip backfill was reinforced with geogrids. An estimated 300,000 waste tire chunks were backfilled in this retaining wall. The WT backfill was covered with a 2 ft (60 cm) soil layer, which was followed by a topsoil/compost mixture.

This wall system was constructed to control rock movement caused by excavation of the toe of a talus slope. The overall stability of the slope would be increased without the construction of a standard concrete wall with soil backfill and incurring extreme expense. The wall units were placed using a small Bobcat excavator with a hydraulic clam on the front. Installation was efficient with minimum problems. Each course was backfilled as it was constructed, and geogrid was used at 2 ft (60 cm) elevation intervals to maintain the integrity of the backfill.

The biggest concern for this retaining wall construction was fire hazards, which occurred soon after completion. The first observation began when heated steam came from the fill at several locations in the area of level 6. Several months later, fire broke out in these locations. Partial explanations for the cause of the fire were auto-ignition of concentrations of white wall parts or tires that were heated by a combination of sunlight, exothermic reaction of compost/sawdust, and geothermal heating in this area.

(4) Maine - The North Yarmouth Field Trial

In this test project, WT chips were used as fill materials beneath a paved road that withstood only low-volume traffic (AADT=1250 with only 10 percent being heavy-duty truck). The two major objectives were to (1) determine the minimum thickness of the soil over the tire chip fill to minimize the pavement deflections to acceptable levels, and (2) study the effects on water quality of WT chips placed above the groundwater table to evaluate environmental impacts due to this application of WT. Other objectives included the construction procedures and quality control for WT chip installation in this road construction. Based on the findings during the construction, complete construction specifications could be developed.

This trial road was divided into five sections, 100 ft (30 m) each. WT fill layers of 2 ft (61 cm) thick were constructed in four of these sections, with a varied thickness of overlying soil cover ranging between 2.5 ft (76 cm) and 4.5 ft (1.37 m) above the tire fill layer. The remaining section was used as a control section that served as a baseline for comparing test results from the WT chip sections. The control section was constructed by using conventional soil fill. All WT chips were encapsulated in a non-woven geotextiles (Amoco 4551) which would permit drainage while preventing the underlying and overlying soil fines from migrating into the WT chip layer. A 5 in (13 cm) of hot mix asphalt was paved on top of all sections. For the monitoring of groundwater quality, three leachate collection basins were installed, two beneath the WT chip layer and the third beneath the control section. These leachate collection systems were used to collect water that had penetrated through the overlying WT chips or soil and the pavement.

WT chips used in the trial project were two types. Type A chips were uniformly graded and had a nominal maximum size of 3 in (7.5 cm). Gradation specifications required that 100 percent passed the 3 in (7.5 cm) square mesh sieve, a minimum of 50 percent passed (by weight) the 2 in (5 cm) square mesh sieve, and a maximum of 20 percent passed (by weight) the No. 4 (0.187 in; 4.75 mm) U.S. standard sieve. Type B chips had a nominal maximum size of 12 in (30.5 cm). Gradation specifications required that the maximum size measured in any direction did not exceed 12 in (30.5 cm), a minimum of 75 percent (by weight) passed the 8 in (20 cm) square mesh sieve, a maximum of 20 percent passed (by weight) the 2 in (5 cm) square mesh sieve. These gradation requirements were not fully met because of some oversized chips. The WT chips were made from a mixture of steel- and glass-belted tires. They were irregularly shaped and had steel belts protruding from the cut edge of the chip. Laboratory testing for the Type A tire chips indicated the loose density was about 25 pcf, and the compacted density with standard Proctor was approximately 40 pcf (Manion, 1992).

The borrow cover over the WT chip sections and over the leachate collection basin in the control section was a well-graded sand with less than 35 percent passing No. 200 (0.00295 in; 0.075 mm) U.S. standard sieve size to have an AASHTO classification of A-2-4. One random gradation test showed that the actual weight of fines passing No. 200 sieve was 12 percent, implying that the borrow cover was a relatively pervious material.

The subbase course material was a gravel, which had a particle distribution like: 25-70 percent passed (by weight) the 1/4 in (6 mm) square mesh sieve, 0-30 percent passed the No. 40 (0.0167 in; 0.425 mm) U.S. standard sieve, and 0-7 percent passed the No. 200 (0.0030 in; 0.075 mm) U.S. standard sieve. The subbase course was 25 in (64 cm) thick, and topped with 5 in (12.7 cm) of asphalt pavement.

The construction began with the installation of the leachate collection basins in the WT chip sections and in the control section. The WT chips were hauled to the site in 40 ft (12 m) long self-dumping semi-trailers, with about 20 metric tons (22 U.S. short tons) in a single trailer load. The WT chips were dumped directly onto the non-woven geotextile. Type A chips were placed and compacted in two 12 in (30.5 cm) thick lifts. A Komatsu D41P track-mounted bulldozer was used to spread the tire chips to meet the grade requirements within 1 in (2.5 cm). Type B chips were better spread as a single 17 to 24 in (43 -61 cm) thick lift. There were difficulties in spreading Type B chips to the specified grade because of significantly large sizes of chip pieces. Type A small-size chips were used to bring this section to within 1" (2.5 cm) of the specified grade.

The smooth drum vibratory roller (Dynamic CA-25, 9 Tons) was considered to be more effective than other compaction equipment in compacting the WT chips. Secondary to it are the tamping foot rollers and the bulldozer. The loaded dump truck proved ineffective because its tires sank deeply into the WT chips and fluffed up the WT chips instead of compacting them. Effectiveness was determined by measuring the settlement of the surface of the WT chips on a grid of 50 points in each section after every two passes of the compaction equipment. Compaction continued until no significant additional increase in settlement was induced. In each section, the total passes were within the specified maximum of 10.

The total weight of WT chips for each WT chip section were precisely recorded during the placement. The in-place densities were then obtained by dividing the total in-place weight of each type of chips by its respective in-place volume. The resulting compacted density was 43 pcf for Type A chips and 38 pcf for Type B chips. These values were comparable to those obtained from the laboratory compaction tests (Nickels, et al., 1995).

The common borrow and granular subbase material were spread in a 12 in (30.5 cm) maximum lift thickness with a small bulldozer, and then compacted to the specified layer depth with a smooth-drum vibratory roller with a static weight of 9 metric tons. Following was the binder and wearing course placement.

A comprehensive monitoring program was established for this trial project. Besides the regular monitoring of leachate for metals and other contaminates, the static pavement deflections with a modified Benkleman Beam, and dynamic pavement deflections with a Road Rater were also measured. Visual pavement surveys have not revealed any abnormal cracking or rutting after completion.