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JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-93/4
Final Report

LABORATORY STUDY ON PROPERTIES OF RUBBER-SOILS

Imtiaz Ahmed

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-93/4
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by

Imtiaz Ahmed
Graduate Research Assistant

Joint Highway Research Project

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and the
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Federal Highway Administration

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May 1993

Final Report
LABORATORY STUDY ON PROPERTIES
OF RUBBER-SOILS

To: Dr. Vincent Drnevich, Director
Joint Highway Research Project

May 12, 1993
Project No. C-36-50L
File No. 6-19-12

From: C. W. Lovell
Professor of Civil Engineering
Purdue University
West Lafayette, Indiana

Subj: Laboratory Study on Properties of Rubber-Soils

Attached is the draft final report on the subject study. The report has been prepared by Mr. Imtiaz Ahmed, Graduate Research Assistant, under my direction.

This study investigates the feasibility of using tire chips, alone and mixed with soils, as lightweight material in highway embankments. The report contains: synthesis of all available information and results from laboratory testing of tire chips, rubber-Ottawa sand, and rubber-Crosby till. The laboratory tests performed on rubber-soils as part of this research included: index, compaction, compressibility, shear, resilient modulus, and permeability. The findings of this study will help the INDOT to determine the feasibility of using waste tires in highway embankments from technical, economic, and environmental viewpoints. Finally, recommendations are made to the INDOT to plan a course of action to share the nation's burden in solving the waste tire problem.

This report is submitted for acceptance in fulfillment of the referenced study.

Respectfully Submitted

Cw Lovell

C. W. Lovell

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16. Abstract

The waste tire problem in the United States is of great magnitude and has far reaching environmental and economic implications. This study investigates the feasibility of using tire chips, alone and mixed with soils, as lightweight material in highway embankments. The report contains: synthesis of all available information and results from laboratory testing of tire chips, rubber-Ottawa sand, and rubber-Crosby till.

It is found that rubber-sand with chip/mix ratios of 38% or less exhibits excellent engineering properties: easy to compact; low dry density; low compressibility; high strength; and excellent drainage characteristics. On the whole, the rubber-Crosby till mixes do not indicate significant promise for use as lightweight geomaterial. The resilient modulus values of rubber-soils are significantly lower than conventional subgrade soils. Long term impact of leachates from tires on groundwater quality is not known.

The use of tire chips and rubber-sand in highway embankments, above the water table, is very promising and should be promoted. The report presents strength and compressibility parameters for design and evaluation of embankments incorporating rubber-soils. In addition, it contains specifications, screening procedures, and testing standards for embankments incorporating rubber-soils.

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TABLE OF CONTENTS

APPENDICES

LIST OF TABLES

Table Page

LIST OF FIGURES

Figure Page

LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway Officials
ASTM	American Society for Testing and Materials
CRA	Crumb Rubber Additive
Cu	Cubic
DOT	Department of Transportation
EPA	Environmental Protection Agency
Ft	Foot/Feet
HMA	Hot Mix Asphalt
DOT	Department of Transportation
INDOT	Indiana Department of Transportation
Mn/DOT	Minnesota Department of Transportation
MPCA	Minnesota Pollution Control Agency
MSW	Municipal Solid Waste
RAL	Recommended Allowable Water Limits
SAM	Stress Absorbing Membrane
SAMI	Stress Absorbing Membrane Interlayer
TCT	Twin City Testing Corporation
USCS	Unified Soil Classification System
US	United States
Yd	Yard(s)

Note: The abbreviations used in the tables are described under each table

TECHNICAL SUMMARY

Indiana Department of Transportation
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May 12, 1993
Laboratory Study on Properties of Rubber-Soils
Imtiaz Ahmed
FHWA/IN/JHRP-93/4

Background

The waste tire problem in the United States is of great magnitude and has far reaching environmental and economic implications. The 1991 Indiana Legislature passed Senate Bill No. 209 and House Bill 1056 dealing with the potential use of waste materials in highways. These bills require the Indiana Department of Transportation (INDOT), in cooperation with state universities, to study the feasibility of using waste tires in road construction. This study is motivated by the INDOT's commitment to promote the use of waste products in highway construction and also to satisfy the requirements of Senate Bill No. 209 and House Bill 1056.

This research investigates the feasibility of using rubber-soils, i.e., a blend of rubber chips and soils mixed in various proportions, in highway embankments as lightweight geomaterial. The report contains: synthesis of all available information; results from laboratory testing of rubber-soils; and a summary of findings. The engineering properties determined as part of this research, include: index properties, compactibility, compressibility, shear strength, resilient modulus, and permeability. Recommendations are made to the INDOT to plan a course of action to share the nation's burden in solving the waste tire problem.

Results

The use of tire chips as lightweight fill material in embankments offers significant technical, economic, and environmental benefits. Potential problems include: large compressibility, fire risk, and undesirable leachates. Detrimental effects of high compressibility can be reduced by using tires under flexible pavements only and letting the chips compress under traffic for some time before placing a final surface course. A soil cover on all sides can provide safety against fire. A recent field study reports that shredded tires show no likelihood of having adverse effects on groundwater quality. However, long term concerns under adverse environmental conditions still persist.

Rubber-sand with chip/mix ratios of 38% or less exhibits excellent engineering properties: easy to compact; low dry density; low compressibility; high strength; and excellent drainage characteristics. The use of rubber-Crosby till mixes in embankments offers some technical benefits, like low dry density and good hydraulic characteristics. However, this material has high compressibility, low shear strength, and is difficult to mix/compact in the field. The resilient modulus values of rubber-soils are significantly lower than conventional subgrade soils.

Conclusions

The use of tire chips and rubber-sand in highway embankments, above the water table, is very promising and should be promoted. A 3-ft soil cap and all-round soil cover is required for safety against fire risk and providing adequate confining pressure to reduce settlements and adverse effects of repeated traffic loads. It is proposed that the strength and compressibility parameters determined as part of this research be used for design and also evaluation of embankments incorporating similar materials, until such time as more extensive testing results are available. A shredded tire test embankment may be planned to determine the long term environmental impacts of using shredded tires as lightweight fill in INDOT facilities. Specifications are given for embankments incorporating rubber-soils.

IMPLEMENTATION REPORT

The waste tire problem in the United States is of great magnitude and has far reaching environmental and economic implications. The 1991 Indiana Legislature passed Senate Bill No. 209 and House Bill 1056 dealing with the potential use of waste materials in highways. These bills require the Indiana Department of Transportation (INDOT), in cooperation with state universities, to study the feasibility of using waste tires in road construction. This study is motivated by the INDOT's commitment to promote the use of waste products in highway construction and also to satisfy the requirements of Senate Bill No. 209 and House Bill 1056.

This study, based on comprehensive laboratory testing and evaluations, assesses the feasibility of using shredded tires in highway embankments as a lightweight fill. The study primarily focuses on determining compaction characteristics, stress-strain-strength behavior and hydraulic properties of compacted rubber-soils. In addition, the study briefly analyzes the environmental impacts and economic benefits of this application of waste tires.

Two types of soils, one each from the fine and the coarse grained family of soils, were selected and prepared for testing purposes. Shredded tire samples of different sizes and gradation were procured from various tire processing agencies. A 6-inch diameter triaxial cell, a 12-inch diameter compaction/compression mold, an 8-inch diameter constant head permeameter, and related accessaries were designed and custom-made/modified for testing of compacted rubber-soils specimens. The MTS soil testing system was used to simulate static and dynamic field loading conditions.

It is found, based on a critical analysis of the available options for reuse, recycling, and disposal of scrap tires, that no single option can solve the waste tire problem in the United States. A comprehensive strategy needs to be developed and pursued to combat this problem at government, industry, and public levels. A comprehensive plan is recommended to reduce the waste tire disposal problem.

The use of shredded tires in highway construction offers technical, economic, and environmental benefits under certain conditions. The salient benefits are: reduced weight of fill - helps increase stability, reduce settlements, and correct or prevent slides on slopes; serve as a good drainage medium, thus preventing development of pore pressures during loading of fills; reduce backfill pressures on retaining structures; allow conservation of energy and natural resources; and can consume large quantities of local waste tires.

Potential problems include: large compressibility, fire risk, and undesirable leachates. Detrimental effects of high compressibility can be reduced by using tires under flexible pavements only and letting the chips compress under traffic for some time before placing a final surface course. A soil cover can reduce fire risk. A recent field study reports that tire chips show no likelihood of having adverse effects on groundwater quality. However, long term concerns under adverse environmental conditions still persist.

Rubber-sand with chip/mix ratios of 38% or less exhibits excellent engineering properties: easy to compact; low dry density; low compressibility; high strength; and excellent drainage characteristics. This rubber-sand mix is useful where significant settlements are unacceptable, e.g., bridge abutments, etc. The use of rubber-Crosby mixes in embankments offer some technical benefits, like low dry density and good hydraulic characteristics. However, this material has high compressibility, low shear strength, and is difficult to mix/compact in the field. The choice of using a mix of tire chips and fine grained soils may be made on a case-by-case basis, depending upon the site conditions. The resilient modulus values of rubber-soils are significantly lower than conventional subgrade soils. Therefore, the use of rubber-soils close to pavement surface may cause excessive fatigue stresses in asphalt pavements.

The cost of using tire chips in embankments depends on many factors that vary with the local conditions, including: cost of chips; the cost of transportation; cost of placement and compaction; incentives offered by the state in the form of subsidies/rebates, etc.; and the cost of conventional mineral/lightweight aggregates. In Indiana, the major vendors of shredded tires are currently willing to provide primary tire shreds without cost. Transportation costs in Indiana vary from $5 to $10/ton for a distance of 100 miles. The exact economic benefits can be determined on a case-by-case basis.

A comprehensive laboratory study is recommended to assess the feasibility of using rubber-soils in loaded and unloaded backfills and in slope stabilization situations. A field study which may include the construction of a test embankment, with adequate monitoring devices, is also recommended. The study will be very helpful in determining long-term performance and development of correlations between laboratory and field parameters.

In summary, the use of tire chips and rubber-sand in highway embankments, above the water table, is very promising and should be promoted. A 3-ft soil cap and all-round soil cover is required for safety against fire risk and providing adequate confining pressure to reduce settlements and adverse effects of repeated traffic loads. It is proposed that the strength and compressibility parameters determined as part of this research be used for design and also evaluation of embankments incorporating similar materials, until such time as more extensive testing results are available. Specifications, screening procedures, and testing standards for embankments incorporating rubber-soils as lightweight geomaterials are proposed for the INDOT.

CHAPTER 1

INTRODUCTION

Both the stability and settlement of embankments across soft soils can be improved by use of lightweight engineered fill (Moore, 1966 and Holtz, 1989). Lightweight materials that have been used in the past as a replacement for conventional materials include wood-chips, sawdust, bark, dried peat, ashes and slags, expanded shale, expanded polystyrene, and cellular concrete (Holtz, et al., 1990). Each of these materials suffer from some disadvantage (e.g., wood is biodegradable and thus lacks durability, certain ashes and slags leach undesirable substances and thus may contaminate the groundwater, and manufactured materials are expensive and are usually produced in low quantities) which makes them less attractive for use as engineered fill in highway structures.

Engineers and researchers have a keen interest in developing civil engineering materials that are environmentally acceptable, more durable, more economical, and are lighter in weight to replace conventional materials in order to enhance stability of slopes/foundations and reduce settlements in problem areas. Certain field and laboratory studies have indicated that these apparently contradictory requirements can be potentially reconciled by the use of rubber-soils, which are defined as a blend of rubber chips obtained from shredding of scrap tires and various locally available soils mixed in various proportions for use in highway structures as lightweight geomaterial.

Various highway agencies, in the United States (e.g., Colorado, Minnesota, Oregon, Vermont, Washington, and Wisconsin) and abroad, have practiced and evaluated the use of shredded tires as a lightweight fill material. Their experience indicated that the use of shredded tires in embankments is feasible and quite beneficial (see Chapter 3). However, information on this application of waste tires is severely lacking. Only a few limited laboratory studies have been reported in the literature.

The 1991 Indiana Legislature passed Senate Bill No. 209 and House Bill 1056 dealing with the potential use of waste materials in road construction. Portions of those bills relate to waste tires. The bills require the Indiana Department of Transportation (INDOT), in cooperation with state universities, to study the feasibility of using waste tires in road construction. The copies of Senate and House bills are included in Appendix A and B, respectively.

The INDOT has been using recycled or waste products for many years in those applications which have been proven effective. They have also researched the use of a variety of waste products in highway construction to find an alternative source of material supply to offset the rising cost of quality natural aggregates, waste disposal, and energy (see Ahmed (1991) for the INDOT's experience in the use of waste products). This study is part of the INDOT's commitment to promote the use of waste product in highway construction and also to satisfy the requirements of Senate Bill No. 209 and House Bill 1056.

The purpose of this research is to investigate, based on laboratory testing and evaluations, the feasibility of using shredded tires and chip-soil mix as lightweight geomaterial in highway embankments. The principal objectives of this study are to: determine stress-stain-strength characteristics of compacted rubber soil samples; analyze results of studies on leachates from waste tires to determine environmental acceptability of using shredded tires in highway embankments; evaluate economic benefits to the INDOT in using shredded tires in place of conventional materials in highway embankment construction; and define screening procedures, testing standards, and specifications for use of shredded tires in embankments. The objectives set forth for this study have been achieved by: synthesizing available information obtained from a comprehensive literature review; conducting compaction, compressibility, triaxial, resilient modulus, and permeability tests on laboratory prepared specimens of tire chips, alone and mixed with soils; and critically analyzing the laboratory data and the results reported in the literature.

Chapter 2 synthesizes the information on recycling, reuse, and disposal options for scrap tires. Published material has been the main source of information. However, in certain cases, material from some unpublished state highway agency reports and research updates are also included to benefit from the findings of recent research studies. Chapter 3 summarizes the characteristics of conventional lightweight materials and rubber tires. It also documents some important field and laboratory studies concerning the use of shredded tires as lightweight geomaterial. Additionally, it contains a discussion and a summary of conclusions.

Chapter 4 describes the testing materials, testing equipment and experimental procedures for compaction testing of rubber-soils. It also presents a summary of the results and discusses the compaction behavior of rubber-soils mixes. Chapter 5 contains a description of the testing equipment, experimental procedures, and a summary of results from the compressibility testing of rubber soils. Analysis of data and salient conclusions are also presented in this chapter.

Chapter 6 gives the stress-strain and strength behavior of laboratory prepared rubber-soils specimens under static loading conditions. The influence of traffic on the behavior of compacted rubber-soils is ascertained by conducting resilient modulus tests. Chapter 7 presents and analyzes the results from the resilient modulus testing of rubber-soils.

The drainage characteristics of engineered fill have pronounced influence on the performance of highway embankments. The coefficient of permeability for tire chips, alone and also mixed with different soils, were determined using a custom-designed large size constant head permeameter. The results are summarized in Chapter 8 of this report.

Chapter 9 summarizes the main conclusions of this experimental study and provides recommendations to reduce the waste tire disposal problem and for further research. It also gives the specifications for construction of an embankment incorporating rubber-soils. A list of references is also included. Three appendices are attached: Appendix A and B are the copies of Senate and House bills, respectively; and Appendix C contains the information about the photograph negatives.

CHAPTER 2

BACKGROUND AND CURRENT TIRE DISPOSAL OPTIONS

2.1 Background

Current estimates by the Environmental Protection Agency (EPA, 1991) indicate that over 242 million scrap tires are generated each year in the United States (see Table 2.1). In addition, about 2 billion waste tires have been accumulated in stockpiles or uncontrolled tire dumps across the country. It is estimated that approximately one tire per person is discarded each year. The current practice in scrap tire disposal indicates that of the 242 million tires discarded annually in the United States, 5% are exported, 6% recycled, 11% incinerated, and 78% are landfilled, stockpiled, or illegally dumped.

The composition of rubber tires makes them bulky, resilient, compaction resistant, and non-biodegradable. Disposal of large quantities of tires has accordingly many economic and environmental implications. Scrap tire piles which are growing each year pose two significant threats to the public: fire hazard - once set ablaze, they are almost impossible to extinguish; and health hazard - the water held

Table 2.1 Scrap tire generation in the United States (after EPA, 1991)
(in thousands)

	Year						
Replacement Tire Shipments	1984	1985	1986	1987	1988	1989	1990
Passenger [1]	144,580	141,455	144,267	151,892	155,294	151,156	152,251
Truck[1]	31,707	32,098	32,392	34,514	33,918	35,172	36,588
Farm Equipment[1]	2,592	2,395	2,319	2,658	2,662	2,664	2,549
Imported Used Tires[2]	1,793	3,233	2,552	2,925	1,352	1,466	1,108
Total Replacement Tires	180,672	179,181	181,530	191,989	193,226	190,458	192,496
Tires from Scrapped Vehicles[3]							
Cars	26,700	30,916	33,768	32,412	35,016	37,200[4]	39,000[4]
Trucks	6,408	8,400	9,236	9,456	9,004	10,400[4]	11,000[4]
Total Tires from Scrapped Vehicles	33,108	39,316	43,004	41,868	44,020	47,600	50,000
Total Scrap Tires in USA	213,780	218,497	224,534	233,857	237,246	238,058	242,496
US Population (thousands)[3]	235,961	238,207	240,523	242,825	245,807	247,732	249,981
Scrap Tires/Person/Year	0.91	0.92	0.93	0.96	0.97	0.96	0.97

Notes:

[1] (includes imported new tiers) National Petroleum News, Fact Book, 1986-1988. Data from the Rubber Manufacturers Association. 1988 through 1990 data from RMA Industry Monthly Tire Report, December 1989 and December 1990.

[2] U.S. Department of Commerce. "U.S. Imports for Consumption." (FT246). 1984-1990

[3] U.S. Department of Commerce, Statistical Abstracts, 1990 and prior years. Estimate based on 4 tires per vehicle.

[4] Estimated by Franklin Association, by linear extrapolation.

by the tires attracts disease-carrying mosquitoes and rodents. Efforts to sharply reduce the environmentally and economically costly practice of landfilling/stockpiling have stimulated the pursuit of non-landfill disposal or reuse of waste tires.

The composition of rubber tires, i.e., integrally combined rubber, synthetic fibers, steel, etc., has made it difficult to separate into ingredients for reuse and has led to unique problems for disposal of tires. However, it has also rendered some useful mechanical properties to this waste product, which has made recycling of tires economically beneficial. Tires are elastic, lightweight, durable, and yield high BTU when incinerated. In addition, recycling of tires has a positive impact on environments. In view of potential economic and environmental benefits associated with the reuse/recycling of waste tires, the use of this product is being experimentally studied for a variety of applications.

Figure 2.1 schematically shows the waste tire generation cycle. From the manufacturer, tires are brought into use through an extensive distribution network to tire dealers. When the initial tread is worn down to the minimum acceptable standard, or when sidewall carcass damage prevents the tire from being used safely, the tire enters the inventory of used

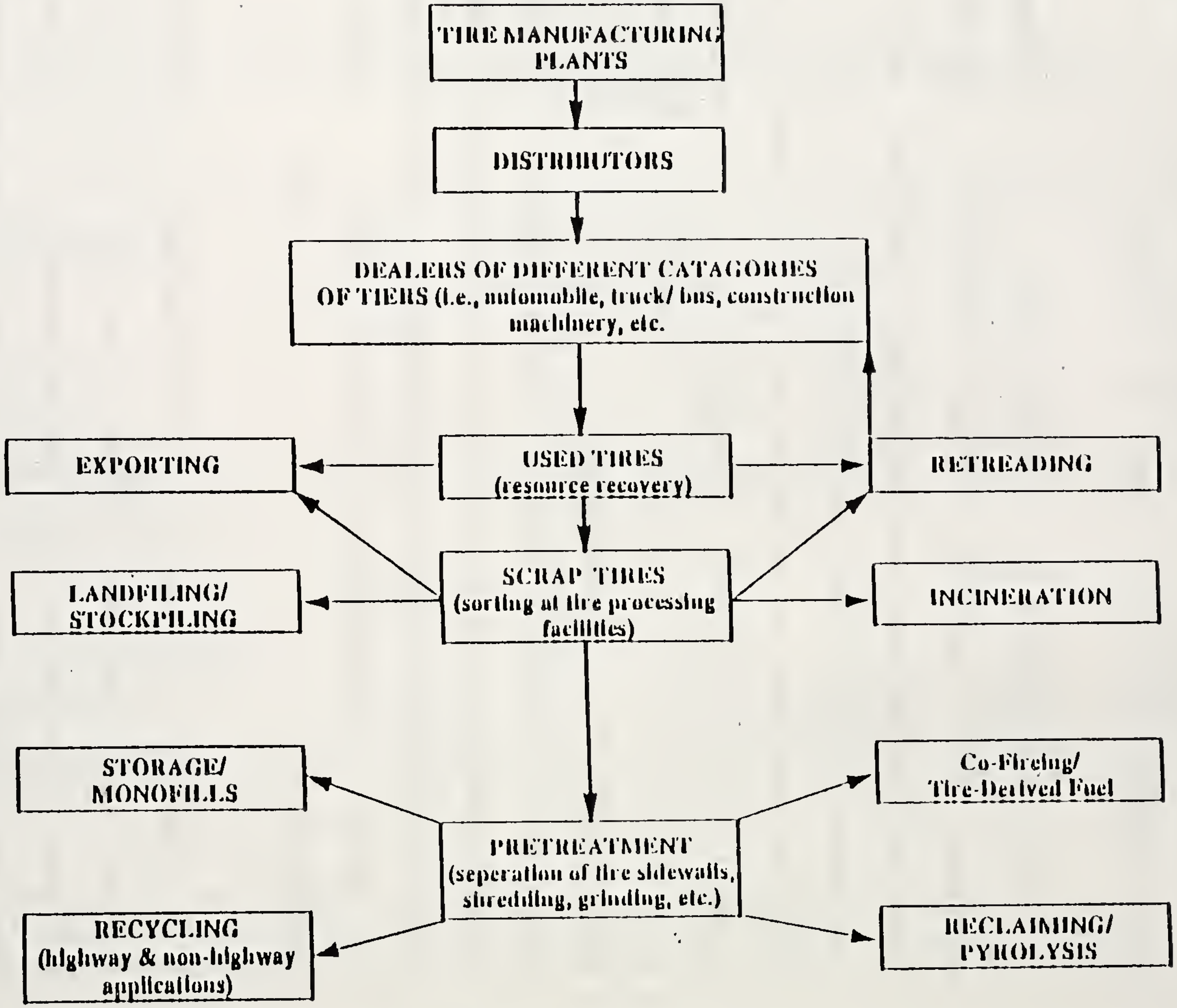


Figure 2.1 Tire manufacturing, retreading, and discards

tires. These tires may be sent to landfills, incinerators, or be chosen as suitable for retreading. The used tires may be sent to tire processing facilities where they are sorted, and those found unsuitable for retreading or exporting may be reduced to smaller size chips through shredding, ground to crumb rubber, or their ingredients may be separated through pyrolysis for reuse in manufacturing plants. The whole tires, shredded tire chips, crumb rubber, and materials reclaimed through decomposition of tires may be used for a variety of engineering applications, which are discussed subsequently.

Efforts to utilize scrap vulcanized rubber dates back to 1858 when Hiram Hall developed the heater pan process for reclaiming natural rubber vulcanizates. The reclaimed product was extensively used, since the reclaiming process was relatively simple and economical (Beckman, et al., 1974). However, as the rubber industry developed synthetic elastomers and the tire industry initiated the use of glass and steel for reinforcement, the reclaiming of scrap tires became progressively more difficult and expensive. The technical advances in tire manufacture have provided a product which is practically indestructible and also difficult to separate into ingredients. These are the leading causes of current tire disposal problems.

Several options are available to solve or minimize the tire disposal problem, including: source reduction by producing longer wearing tires, retreading and reuse of scrap tires; incineration of tires with generation of energy; recycling of whole tires for construction of various products; and processing the tires for use in a variety of applications. Some of these options have been investigated over the years within the United States and abroad. The following subsection gives an overview of current practice in the United States in the use of scrap tires in highway construction. The various options available for the reuse, disposal, and recycling of scrap tires are then described in some detail in the subsequent subsections. Finally, this chapter also gives a brief discussion on the various uses of waste tires and a summary of conclusions.

2.2 An Overview of Current Practice in the Use of Rubber Tires in Highway Construction

The technology for the use of rubber tires in a variety of highway applications has been developed over many years in the past. The whole tires have been used, with some success, for soil retaining, erosion control, and construction of sound/crash barriers. The highway industry has also investigated the use of three products reclaimed from scrap tires, which include crumb rubber, shredded tires, and tire sidewalls. Addition of crumb rubber in asphalt produces a binder with improved mechanical properties. This binder (called asphalt-rubber) is used in asphalt paving products, including crack/joint sealant, surface/interlayer treatments, wearing courses, etc. In addition, crumb rubber is also added to specially graded aggregates to produce rubber modified asphalt mixtures. Shredded tires are incorporated in embankments mainly to reduce the weight of fill across soft foundation areas. Mats of tire sidewalls have been used in embankments to reinforce the fill material. The concept of using tires in embankments is also extended to enhance the stability of steep slopes (see Ahmed and Lovell, 1992).

Recently, the author conducted a synthesis study (Ahmed, 1991) to identify those waste materials which have demonstrated technical, economic, and environmental feasibility for use in highway construction. The questionnaire survey conducted as part of this study indicated that of the 44 state highway agencies responding to the questionnaire, 30 states are currently using or experimenting with the use of rubber tires in a number of highway applications. A majority of states reported the use of crumb rubber additive (CRA) in asphalt paving products as a binder (asphalt-rubber) and/or as an aggregate (rubber modified asphalt). A few states reported their experience with the use of shredded tires in embankment/subgrade as a lightweight fill material (e.g., Minnesota, Oregon, Vermont, and Wisconsin). The California State Department of

Transportation reported the use of whole tires and tire sidewalls for soil retaining and for soil reinforcement, respectively.

Legislation which is intended to stimulate recycling of tires is in force in a number of states and is being debated in others. As of January 1991, thirty six states have passed or finalized scrap tire laws or regulations, and all but 9 states regulate or have bills being proposed to regulate tires (EPA, 1991). The majority of states have imposed regulations that require tires to be processed (cut, sliced, or shredded) prior to landfilling. Disposal of whole tires in landfills is discouraged (in almost all cases) either by law (e.g., Minnesota) or more frequently by high disposal fees. Four states (i.e., Oklahoma, Oregon, Utah, and Wisconsin) have developed rebate programs to encourage recycling or burning for energy, helping stimulate the scrap tire market.

The respondent state highway agencies had generally reported approximate annual quantities of waste materials currently used, which indicated that rubber tires are generally used in small quantities, with a few exceptions (e.g., Arizona, Oregon, and Vermont state highway agencies). The state highway agencies also reported their experiences with the use of waste tires in highway construction from technical, economic, and environmental viewpoints. The author also synthesized the information reported in the literature on the performance of waste tires in highway construction (Ahmed, 1991).

Based on a critical analysis of the information obtained as a result of the questionnaire and a review of the literature, the following conclusions were drawn concerning the use of waste rubber tires in highway construction (Ahmed, 1991 and 1993):

1) Use of asphalt-rubber as a crack/joint sealant seems cost effective in view of its better performance in most of the cases. However, its long term performance must be monitored due to lack of sufficient experience with its use.
2) Use of Stress Absorbing Membranes (SAM) reduce the reflection of fatigue cracks of moderate width and thermal cracks; has generally provided longer service life than the conventional surface treatments; and is likely to be equal to the conventional surface treatment on a life cycle cost basis.
3) Stress Absorbing Membranes Interlayers (SAMI) have generally not been effective in eliminating the reflection of fatigue cracks. Although some reduction in reflection of cracks has been

experienced, the improved performance is not commensurate with the additional cost.

4) Asphalt-rubber and rubber modified asphalt mixtures in asphalt pavements have met with both successes and failures. The products need to be further researched to fully understand their behavior prior to their extensive use in the highway industry.

5) The initial cost of the asphalt paving products with CRA are generally 50% to more than 100% higher than the products with conventional materials, depending upon the local conditions. The additional cost may be justified over the life cycle, if long term evaluations show that asphalt-rubber and rubber modified asphalt paving products perform better than the conventional materials and provide longer service lives, which is generally not substantiated by field experience at present.

6) The use of CRA in asphalt paving products is generally acceptable from an environmental viewpoint, with some concern about air pollution as a result of adding rubber to the mix and also the requirement of elevated temperatures during mixing of paving materials.

7) The use of shredded tires in subgrade/embankment as a lightweight fill material is technically feasible and economically beneficial, as tires are non-

biodegradable and large quantities of waste tires can be so consumed. Potential problems include leachates of metals and hydrocarbons. It was found that drinking water Recommended Allowable Limits (RALs) were exceeded under "worst-case" conditions (MPCA, 1990).

8) The use of tires for soil reinforcement in highway construction is feasible from technical and economic viewpoints, but may have environmental implications.

9) The use of tires in retaining structures is economical and practical, but has aesthetic and environmental implications.

10) Feasibility of recycling asphalt paving products containing CRA is not known, due to limited reported experience.

2.3 Source Reduction

Source reduction, i.e., reducing the number of tires generated in the first place, is one of the options to be considered to minimize the tire disposal problem. Source reduction measures for tires include:

1) Design of longer wearing tires - The development of radial tires and advances in technology have more than doubled the life of tires over the past forty years. Currently 40,000 miles is the usual life of

a steel belted radial passenger tire, and sixty to eighty thousand mile life times may be achieved with proper care and maintenance. Further increase in life would require higher pressure, thicker treads, or less flexible materials. Each of these methods would result in more gas consumption, higher cost, and/or rougher rides. It is, therefore, not expected that any major changes will occur in the near future that will significantly increase tire life (EPA, 1991).

2) Reuse of used tires - Generally, when one or two tires of a set are worn, the entire set is replaced with new tires. The reuse of those tires that still have serviceable treads can reduce the tire disposal problem. EPA (1991) estimates indicate that currently about 10 million tires are reused, and that reuse could potentially double based on the number of waste tires generated.

3) Retreading - Retreading is the application of a new tread to a worn tire that still has a good casing. Retreading of worn tires is an efficient, viable procedure for recycling. Retreading began in the 1910's and about 33.5 million tires (18.6 million passenger/light truck and 14.9 million truck tires) were retreaded in 1990. There are over 1,900 retreaders in the United States and Canada; however

the number is shrinking because of the decreased markets for the retreads (EPA, 1991). The decline is primarily due to the low price of new tires and the common misconception that retreads are unsafe. Conversely, truck tire retreading is increasing; such tires are often retreaded three times.

2.4 Recycling of Whole Tires and Tire Sidewalls

2.4.1 Soil Reinforcement

Engineers and researchers have a keen interest in methods of reinforcing soil by inclusions possessing tensile strength, and in developing civil engineering materials that are more economical, but otherwise comparable with existing materials. These two apparently contradictory requirements can now be reconciled by the use of rubber-soils. Various agencies, in the United States and abroad, have tested and evaluated the use of tires for soil reinforcement. Forsyth and Egan (1976) described a method for the use of waste tires in embankments and considered it a very promising application. The method involves separation of tire sidewalls and treads, the latter being a commercially valuable commodity. The tire sidewalls can be used as mats or strips in embankment to increase its stability.

The laboratory and theoretical studies conducted by Caltrans (Forsyth and Egan, 1976) indicated that the systematic inclusion of tire sidewalls could possibly strengthen a fill and thus permit steeper side slopes and increase resistance to earthquake loading. Encouraged by the results of these studies, Caltrans designed a tire-anchored wall system, in which tire sidewalls were used to anchor timber retaining structures (Richman and Jackura, 1984; TNR, 1985 and Caltrans, 1986). They are now developing designs to incorporate 6 ft. timber posts obtained from the removal and replacement of guardrail installations.

Construction Incorporated, Youngstown, Ohio, used an innovative method of constructing a road across a swampy area near Niles, Ohio (Biocycle, 1989). They used tire sidewall mats linked with stainless steel strapping as a foundation and found it a practical and economical way of constructing roads across soft patches. The method has been patented under the trade name "Terramat". It is reported that the Terramat system is economical in the areas of soft, unstable, and waterlogged ground. The system is found uneconomical in those areas where embankment foundation soil is strong and does not present a stability problem.

Turgeon (1989) described the experience of the Minnesota Department of Natural Resources in the use of tires for soil reinforcement. They used whole tire mats and tire chunks as a material to replace corduroy logs for road embankments over swamps. This technology is reportedly spreading to other roadway projects.

In France, a technique to reinforce soil using scrap tires has been developed recently, which is patented under the trade name "Pneusol" (i.e., Tiresoil). The first research in France on the use of old tires to reinforce soils was done in 1976 (Audeoud et al., 1990), which finally led to the development of "Pneusol". It is a combination of soil and tire parts, which may be tied together in chains or placed in layers. The engineering properties of Tiresoil have been studied by the French engineers and the mix has been found suitable for construction of embankments and retaining walls. Tiresoil is found to improve the mechanical properties of soil either anisotropically, i.e., only in the direction in which the material is most highly stressed (layers, linear strips, etc.), or isotropically, i.e., in all directions (the elements are mixed with soil).

This application of waste tires is considered practical and economical, but it may have environmental implications (as discussed in Chapter 3). The potential problem include leachates of metals and hydrocarbons. Further research is required to develop/standardize design and construction procedures and also determine the long term effects on the groundwater quality of using tires in subgrade/embankment.

2.4.2 Soil Retaining

The use of tires in retaining structures has also been practiced primarily for maintenance and rehabilitation of road embankments (Caltrans, 1988; Nguyen and Williams, 1989; and Keller, 1990). Whole tires anchored in the backfill are used in various configurations for wall heights up to 10 ft. This application is economical, results in moderate face settlement and may have aesthetic and environmental implications.

2.4.3 Erosion Control

Scrap tires lashed together forming large mats have been used to control erosion along highway slopes, coastal roads, drainage channels, etc. The California Office of Transportation Research has investigated several erosion control applications of scrap tires. Discarded tires were banded together and partially or completely buried on unstable slopes in tests conducted between 1982 and 1986. They found this application of waste tires practical and economical. Construction costs were reduced from 50 to 75 percent of the lowest cost alternatives such as rock, gabion, or concrete protection. It is reported that less than 10,000 tires are used annually for this application in California (EPA, 1991; Nguyen and Williams, 1989; and Williams and Weaver, 1987).

Scrap tires have also been used for shoreline protection. On the eastern shore of Maryland, a scrap tire revetment has been constructed by stacking tires four high and anchoring the tires into the ground with fiberglass pins. The cavity is filled with soil and a plug of dune grass to promote vegetation and hide the revetment. The method appears to be successful in coastal areas with moderate tides and limited wave action. The costs are estimated at about $40 per linear foot compared to about $100 per linear foot using conventional shoreline protection methods (Crane, et al., 1978).

2.4.4 Sound Barriers

Rubber tires have good sound insulation characteristics. The Wisconsin Department of Transportation has recently constructed an embankment along a highway to investigate the use of tires for noise reduction. If their trials support this usage of tires, large quantities of scrap tires can be consumed in this application along highways passing through major cities or built up areas. However, proper coverage of the tires would be required to provide safety against fires and for aesthetic purposes.

2.4.5 Crash Barriers

The use of scrap tires as crash barriers was investigated in the late 1970's by the Texas Transportation

Institute. They found that stacked tires bound together by a steel cable and enclosed with fiber glass would reduce or absorb impact of automobiles traveling up to 71 miles per hour (Hirsch and Marquis, 1975; Marquis, et al., 1975; and Caltrans, 1975). Their report concluded that it was both technically and economically feasible to use scrap tires as vehicle impact attenuators. However, this application of waste tires has not been very popular basically for two reasons: (1) on impact the tires are likely to spill onto the highway and may be a safety risk for other traffic, especially from the opposite direction; and (2) the highway community generally prefers sand-filled crash barriers because they have excellent absorption characteristics and are easier to construct.

2.4.6 Breakwaters

Breakwaters are off-shore barriers that are constructed to protect the harbor or shoreline from the full impact of the waves. Breakwaters using scrap tires were tested by US Army Corps of Engineers and were found to be effective for smaller waves (EPA, 1991). Floating breakwaters have also been investigated, and are found to be more effective (OECD, 1980). Floating breakwaters are constructed by partially filling tires with foam rubber, and lashing them together in modular bundles. They have excellent energy absorbing characteristics. The cost estimates vary and depend on: the design life; material, labor, and transportation costs; and local conditions.

2.4.7 Artificial Reefs

Waste rubber tires have been used to build artificial reefs to provide homes for all sorts of aquatic life. Scrap tires are preferred for this application because of many factors, including: their low cost, longer service life, large surface area, ease of design and construction, and a convenient method to dispose of large quantities of tires. The United States Bureau of Sport, Fisheries, and Wildlife (BSFW) has been experimenting with artificial reefs made from used tires since 1965. BSFW estimates that artificial reefs could absorb all scrap tires generated in the United States. Malaysia is currently seeking 35 million tires to use as a breakwater barrier and reef (Ruth, 1991). However, artificial reefs are labor intensive and quite expensive to construct. The estimated reef construction cost is $2.69 per tire, including collection, handling, and transportation costs (OECD, 1980). The benefits of artificial reefs include: increased recreational fishing facilities, avoiding tire disposal costs, positive impact on environments, and stimulating commercial fisheries. However, the long term effect of artificial reefs on the ocean environment is unknown.

2.4.8 Splitter Industry

The splitter industry utilizes scrap tires that are rejected by retreaders. The industry is mature and dates back to 1915. They use approximately 50 million pounds of scrap tires per year to manufacture useful articles such as gaskets, shims, or ribbons from which floor mats and dock bumpers are fabricated. This usage is equivalent to about 3 million scrap tires. Although a good growth rate is predicted, the volume of scrap tires used by this industry will not absorb a large percentage of the supply (OECD, 1980).

2.4.9 Landfilling/Stockpiling

Burying tires in landfills has been the most common method of tire disposal in the past. However, tires occupy a large landfill space due to low bulk density and they have a tendency to rise up to the surface. In addition, existing landfills are fast diminishing and new landfills are difficult to site. In Indiana, 12 years ago, there were 150 landfills. These have diminished to 78, with a life span of less than seven years each. Several states have considered or are considering legislation that would completely ban disposal of whole tires in landfills. Landfilling of whole tires is discouraged either by law or more often by high disposal fees, or by requiring that tires be disposed of in tire monofills.

Stockpiling of tires may be unsightly and hazardous. Tire stockpiles hold stagnant water which provides an ideal breeding ground for disease carrying insects and vermin. The most obvious hazard in stockpiling is the potential for fire. In 1984, a 1.5 million tire stockpile caught fire and burned out of control for seven months (Civil Engineering, 1989). The fire left 5 acres of ash and metals containing hazardous waste which proved to be extremely difficult to clean up by conventional methods. The environmental and economic problems associated with landfilling and stockpiling of scrap tires have stimulated the search for non landfill disposal, recycling, and reuse of scrap tires.

2.5 Shredded Tires Applications

Tires are shredded for several applications, including shredding prior to landfilling/incineration. The majority of scrap tire disposal procedures require some degree of size reduction. A significant transportation and handling cost savings can be realized by increasing the bulk density of scrap tires, i.e., by size reduction. Several types of commercial choppers/shredders have been developed, which can reduce a tire, including beads and steel-belts, to a particle range of several centimeters to fractions of a centimeter. The larger particle size range is generally required if the scrap rubber is to be landfilled. The small particle size range is generally used when the scrap rubber is to be further processed for various applications, including crumb rubber production. Some of the applications of shredded tires, which have been used over the years with varying degrees of success, are described below.

2.5.1 Lightweight Fill

Construction of roads across soft soil presents stability problems. To reduce the weight of the highway structure at such locations, wood-chips or saw dust have been traditionally used as a replacement for conventional materials. Wood is biodegradable and thus lacks durability. Conversely, reclaimed rubber tires are non-biodegradable and thus are more durable. Other potential benefits of using shredded tires as lightweight fill in embankments founded on weak, compressible foundations are: reduced weight of fill; generally an economical alternative to conventional materials; a free draining material, so there are no problems with build up of excess pore pressure; conservation of natural resources; and recycling of large quantities of locally available waste tires. Tire chips can replace the existing material in a slide prone areas to reduce the weight on foundation soil, and thus improve stability of slopes.

Various agencies, in the United States and abroad, have evaluated the use of shredded tires as lightweight fill material in a variety of different ways, i.e., chips mixed with soils, layered with soils, or pure chips. Their experience and findings from the research support the use of properly confined tire chips in highway applications (Chapter 3 summarizes the experience and research in the use of chips as lightweight fill). This application of waste tires is considered practical and cost effective (cost of tire chips is generally competitive with wood chips). However, it may have environmental implications, as discussed in Chapter 3.

2.5.2 Synthetic Turf

The feasibility of using scrap rubber as a component in synthetic turf for playgrounds, factory floors, park paths, etc., has been investigated in the past. Goodyear announced a new product called Tire Turf (Anderson, 1972) which is prepared by mixing shredded tires (bead-free) with a binder, such as polyurethane, latex, or asphalt. The Tire Turf is laid like concrete and cures overnight. The turf has good anti-slip properties and can be placed around swimming pools. The turf is usually covered with a fireproof material and is stated to be both fungus- and rot-proof. Long term durability data concerning this material are not available.

2.5.3 Playground Gravel Substitutes

Some of the companies (e.g., Baker Rubber, Inc., South Bend, Indiana; Waste Reduction Systems in Upper Sandusky, Ohio; and Safety Soil of Carmichael, California) are producing tire chips for use as gravel substitute in playgrounds and running tracks. Tires are shredded to sizes ranging from 1/4 in. to 5/8 in. All steel from the tire chips is removed by using magnets. The benefits of using rubber chips in and around playground equipment include: provide a better cushion than conventional materials, i.e., gravel, stones, wood, etc.; are more durable; provide cleaner environments; are free draining material; and are cost competitive on a life cycle basis. However, tire chips have a higher initial cost and are potentially combustible, thus requiring additional precautions against fire.

2.5.4 Oil Spills

Shredded rubber tires in combination with polystyrene scrap have a good capacity for absorbing oil and can be used for cleaning up oil spills (Beckman, et al., 1974). After absorbing oil, the mixture is heated to form an asphaltic material that is claimed to be useful for road building (to avoid a secondary disposal problem).

Koutsky, et al. (1977) conducted a laboratory study to determine the oil absorbing capacity of rubber particles. They used rubber particles sizes ranging from the #70 sieve to #20, obtained from a cryo-hammer mill process using old tires as the stock material. They experimented with rubber particles alone and with rubber particles mixed with wood fines. They found that the oil up-take of rubber particles was affected by particle size, temperature and type of oil. Mixing of rubber with wood shavings imparts cohesion to the mix, which facilitates drawing the mix into a collection device. The study concluded that rubber particles can be efficiently and economically used for oil spill recovery.

2.5.5 Shredded Tires as Mulch

Traditionally, wood chips or straw have been used as mulch for landscaping along highways. Shredded tire chips can also be used for this purpose. Tire chips are more durable and would require less frequent replacement. However, steel will have to be removed from the chips, which is likely to make this product more expensive than wood chips.

2.5.6 Building Products

Rubber Research Elastomeric of Minneapolis produces a product called Tirecycle, made from shredded tires and new rubber, for use in automobile truck liners, floor mats, and dashboards (Cindy, et al., 1990).

Another waste tire recycling process being developed is called "reclassification" and involves shredding, pyrolysis (see Subsection 2.5.8), and purifying tire components, and results in by-products of carbon black, oil, and gas. This is a patented commercial process developed by American Tire Reclamation, Inc. This company has plants in Oregon, Ohio, and Pennsylvania, each of which are expected to process about 5,000 tires per day (Cindy, et al., 1990).

Research is underway on a variety of products using reclaimed shredded rubber to produce items such as containers, plants, fence posts, and domestic drain pipes. J & J Trading, Inc. of Chester, Pennsylvania claims that the shredded rubber is cheaper than any raw material used to manufacture drain and sewer pipes (Elastomerics, 1989).

2.5.7 Chemical Uses

Chemical uses of scrap tires include the controlled chemical treatment of scrap tires permitting the recovery of certain original or related chemical constituents. All chemical processes involve the initial reduction of whole tires to smaller sized chips. The chemical composition of a scrap tire as expressed by product or element analysis is quite variable and is difficult to specify. However, major components of a typical worn (steel-free) tire are: rubber (50%), carbon black (27.5%), and oil (17.5%). An approximate chemical analysis of a scrap tire is carbon, 83%; hydrogen, 7%; oxygen, 2.5%, sulfur, 1.2%; and nitrogen, 0.3%. The remaining is nonvolatile ash (Crane, et al., 1978).

1) Destructive Distillation, Carbon Black Recovery and Hydrogenation - It is possible to recover the various constituents of scrap tires, using various chemical processes. Two of the processes, i.e., destructive distillation and carbon black recovery, are forms of pyrolysis. Hydrogenation is a process of chemical synthesis. It involves addition of hydrogen to rubber to make chemicals from which new elastomers can be produced. In pyrolysis, tire ingredients (i.e., carbon, hydrogen, ash) are yielded in chemically complex oils and gases, and a solid residue. Depending on the operating temperature, the proportion of oil, gas, and residue can be varied. High temperature (i.e., 900°C) pyrolysis yields large quantities of residue, much of which is carbon black. Whereas, lower temperature pyrolysis yields large quantities of oils, mostly olefins, aromatics, and naphthenes (OECD, 1980). Pyrolysis of waste tires is a rapidly developing technology. The rising cost of petroleum feedstocks for producing elastomers and recycling of waste tires are the main incentives for improving the process. Although, many experimental pyrolysis units have been tried, none has yet demonstrated sustained commercial operation (EPA, 1991).

2) Reclaimed Rubber - A commercial description or definition of reclaimed rubber is: the product resulting from the treatment of ground vulcanized scrap rubber tires, tubes and miscellaneous waste rubber articles by the application of heat and chemical agents, followed by intense mechanical working, whereby a substantial "devulcanization" or regeneration of the rubber component to its original plastic state is effected, thus permitting the product to be compounded, processed and revulcanized (Smith, 1978). Reclaiming is essentially depolymerization; the combined sulfur is not removed. The product is sold for use as a raw material in the manufacture of rubber goods with or without admixture with natural or synthetic rubber. The market for reclaimed rubber depends upon its cost of production and upon its quality relative to virgin rubber. The relatively small proportion of reclaimed rubber used in new tire production is due to a technological problem. With existing blending technology, reclaimed products cannot be used in proportions greater than 1% to 2% for higher performance tires (OECD, 1980).

3) Asphalt and Fuel Production - The New Paraho Corporation of Denver, Colorado, has initiated a

program to investigate the feasibility of producing high quality asphalt and fuel from the pyrolysis (destructive distillation) of oil shale with five percent scrap tires. The concept is to market the asphalt as an additive to improve the properties, particularly moisture susceptibility, of standard petroleum-based asphalts, and thereby make the process cost effective. The potential benefits associated with the co-processing of spent tires with oil shale include the relatively high oil content of tires per unit weight in comparison to oil shale and the higher percentage of naphtha (gasoline), making this oil more valuable as a refinery feedstock. A pilot plant has been built to investigate the properties of this co-processed material. If the pilot plant study shows the process is profitable and a full-scale plant is built, it is likely to consume most scrap tires produced in the state of Colorado (Cindy et al., 1990).

2.5.8 Storage/Monofills

Landfilling of whole tires is discouraged in almost all the states. Whereas, stockpiling of whole tires is hazardous (see Subsection 2.2), a majority of states have imposed regulations that require tires to be processed (cut, sliced, or shredded) prior to landfilling. However, this is wasteful of the country's natural resources. Kurker (1977) has suggested a procedure for stockpiling whole or chopped scrap tires until economical processes are commercialized. In the writer's opinion, monofills of shredded tires may be a comparatively better option than landfilling/stockpiling of whole tires. The possible advantage to this arrangement would be time, allowing a disposal technology to be forthcoming that would convert the scrap tires to a high-value product. However, shredding would cause additional costs and proper preventive measures would be required against fire, since stockpiles would be a great fire hazard.

2.6 Crumb Rubber Technology

2.6.1 Crumb Rubber Production

The most common technology used to convert scrap tires into crumb rubber is with shredders and grinders operated at ambient temperatures. There are currently 15 companies in the United States which produce crumb rubber through ambient grinding (Spencer, 1991). These facilities use various combinations of shredders, magnets, granulators, cracker mills, and screening equipment to produce crumb rubber, steel, and fiber from scrap tires.

Crumb rubber is produced basically using three methods (Heitzman, 1992): 1) crackmill process - this process tears apart scrap tire rubber, reducing the size of the rubber by passing the material between rotating corrugated steel drums and it is the most common method; 2) granulator process - shears the scrap tire rubber, cutting the rubber with revolving steel plates that pass at close tolerance; and 3) micro-mill process - which further reduces a crumb rubber to a very fine particle size. As the scrap tire rubber is processed, reducing its size, the steel belting and fiber reinforcing are separated and removed from the rubber. Typically, 50% to 60% of crumb rubber is recovered from scrap tires.

Each method of producing crumb rubber generates unique particles with specific characteristics. The cracker mill process produces an irregularly shaped torn particle with a large surface area. The particles can be produced over a range of sizes from 4.75 mm to 425 μm (sieve No. 4 to No. 40), commonly described as a ground CRA. The granulator produces a cubical, uniformly shaped cut particle with a low surface area. Typical range of particles sizes is from 9.5 mm to 2.00 mm (3/8 in. to sieve No. 10). This material is called a granulated CRA. The micro-mill process produces a very fine ground CRA, with particles sizes ranging from 425 μm to 75 μm (sieve No. 40 to No. 200; Heitzman, 1992).

Tires can also be ground by a "cryogenic" method.

Cryogenics is defined by the Webster's Dictionary as "the science that deals with the production of very low temperatures and their effects on the properties of matter." When extremely cold conditions are applied to tires, usually with liquid nitrogen, the rubber is cooled to a point where it becomes brittle.

In a typical crumb rubber production plant using the cryogenic method, the cooled tire pieces drop into a hammermill to be fractured into crumb rubber, steel, and fiber. A shaking screen separates fiber and steel from the rubber granules; a magnetic separator removes steel. Next, the rubber granules are transported by a conveyor/dryer to remove excess moisture, which allows easier separation of remaining fiber, and separation of rubber granules by particle size. The complete rubber granules stream passes through a secondary magnetic separator and then is classified by means of a shaker screen into various mesh sizes ranging from greater than sieve No. 5 to less than sieve No. 40. The oversized material is then processed through a granulator to reduce the particles to the desired gradation. The principal benefit reported from cryogenic grinding is that the product is not thermally and/or oxidatively degraded to any appreciable extent (Crane, et al., 1978).

2.6.2 Crumb Rubber in Asphalt Paving Products

"Crumb Rubber Additive" (CRA) is the generic term for the product from scrap tires used in asphalt products. It is the product from "ambient" grinding of waste tires and retread buffing. Tires ground by the "cryogenic" method can also be used in asphalt. However, mixed opinions are expressed about their suitability as CRA (Bernard, 1990; Biddulph, 1977). Addition of CRA to asphalt paving products can be divided into two basic processes: (1) wet process - blends CRA with hot asphalt cement and allows the rubber and asphalt to fully react in mixing tanks to produce an asphalt rubber-binder; (2) dry process - mixes CRA with the hot aggregate at the hot mix asphalt (HMA) facility prior to adding the asphalt cement to produce a rubber modified asphalt mixture. The four general categories of asphalt paving products which use CRA include: crack/joint sealants, surface/interlayer treatments, HMA mixtures with asphalt-rubber, and rubber modified HMA mixtures.

2.6.3 Crack/Joint Sealant

This may be an asphalt-rubber product, blending 15% to 30% CRA with the asphalt cement. It is covered in the American Society for Testing and Materials (ASTM) specifications (ASTM D3406) and it is routinely used by many state highway agencies. The performance of asphalt-rubber as a crack/joint sealant is generally found to be satisfactory.

Asphalt-rubber crack/joint sealant is typically preblended and packed in 50lb blocks. These blocks are remelted and "reacted" before the sealant is applied. Stephens (1989), based on nine-year evaluations of field performance of asphalt-rubber as joint sealant, reported that site-mixed materials performed better than pre-mixed materials.

2.6.4 Surface/Interlayer Treatments

Surface/interlayer treatments may use an asphalt-rubber binder with 15% to 30% CRA. This application of CRA began in the late 1960s and was patented under the trade name SAM (Stress Absorbing Membrane) and SAMI (Stress Absorbing Membrane Interlayer).

1) SAM - It is a trade name for a chip-seal with an asphalt-rubber sealant. The purpose of this layer is to seal the underlying cracks, thereby preventing the entry of surface water into the pavement structure. It is also intended to absorb the stresses that would lead the underlying cracks to reflect up to the surface. It is formed by applying asphalt-rubber on the road, covering it with aggregate and seating the aggregate with a roller. The thickness of the application usually varies from 3/8 to 5/8 in. (Singh and Athay, 1983), and 0.5 to 0.65 gallons per square yard of binder

is applied to the surface. Another approach to the construction of a SAM is to proportion and mix the asphalt-rubber material and chips in a conventional asphaltic concrete spreading machine. However, the cast-in-place SAMs have performed better (Vallerga, et al.,1980).

2) SAMI - It is a layer, with an asphalt-rubber binder, sandwiched between the road base and an overlay. The only difference between SAM and SAMI is that SAM does not have an overlay whereas SAMI does. The intended purpose of SAMI is to reduce reflection cracking by cushioning or dissipating the stresses from the underlaying pavement before they are transferred to the overlay. The procedure in placing the SAMI is similar to that used in placing the SAM, with a few differences in design aspects.

3) Impermeable membranes - The concept of SAMIs has been extended to the use of impermeable asphalt-rubber membranes, that are laid between subgrade and subbase/base, and have proved successful for controlling moisture in subgrade soils. The membranes help reduce evapotranspiration of moisture from the subgrade and infiltration of

moisture from surface runoff. In the case of expansive soils, variations in moisture content can lead to large volume changes, which may cause development of cracks in the pavement, thus reducing pavement service life and also creating hazardous driving conditions. The asphalt-rubber membranes have been used on northwestern Arizona highways, which are mostly laid on expansive clays (Walsh, 1979). Field observations and objective measurements indicate that the membrane treatment has improved pavement performance.

2.6.5 Asphalt-Rubber Mixtures

The use of asphalt-rubber binder in HMA mixtures has been researched in the USA for the past 40 years. In the early 1960s, Charles McDonald, Materials Engineer for the City of Phoenix began working with a local asphalt company, Sahuaro Petroleum, to develop a highly elastic maintenance surface patch using CRA. In 1968, the Arizona Department of Transportation (DOT) placed its first SAM (Scofield, 1989). The Arizona DOT placed its first SAMI in 1972 and used the CRA modified binder in HMA open graded friction course in 1975. As the Sahuaro technology continued to expand, the Arizona Refinery Company (ARCO) developed a similar "wet process" technology which added a blend of CRA and de-vulcanized CRA to the asphalt cement. Eventually the Sahuaro and ARCO technologies merged and are presently controlled by the patents' co-owners. Today, the "wet process" developed in Arizona, is referred to as the McDonald technology. The amount of CRA in asphalt-rubber binder for HMA applications generally ranges from 15 to 25 percent by weight of asphalt cement (Heitzman, 1992).

Conventional Marshall and Hveem mix design procedures have been used successfully for dense graded mixes using McDonald's asphalt-rubber technology. The characteristics of the modified binder alter the laboratory measured properties of the mix and should be considered while designing these mixes. Typically, the increase in the design binder content is proportional to the amount of CRA in the binder. The design concept being developed for modified gap graded mixes is to maximize the asphalt-rubber content of the mix. Typical asphalt-rubber content for gap graded mixes ranges from 8 to 9 percent (Heitzman, 1992). The reported benefits of using asphalt-rubber HMA mixes include (McQuillen and Hicks, 1987): flexibility down to -26°C (-15°F); higher viscosity than conventional asphalt at 60°C (140°F); tougher (in relation to surface wear from studded tires) and a more elastic surface; greater resistance to aging; and recycling of used tires.

2.6.6 Rubber Modified Asphalt

The concept of introducing coarse rubber particles into asphaltic pavements (using the dry process) was developed in the late 1960s in Sweden. It was originally marketed by Swedish Companies under the patented name "Rubit". This technology was introduced in the United States in the 1970s as the patented product, PlusRide (Bjorklund, 1979; Allen and Turgeon, 1990). The Alaska DOT began working with PlusRide in 1976 and is still the principal highway agency developing this technology. Three corporations have marketed the PlusRide technology since it was introduced in the United States, presently it is the PAVETECH Corporation (Heitzman, 1992).

The PlusRide process typically uses 3% by weight granulated coarse and fine rubber particles to replace some of the aggregates. The mix design for PlusRide does not follow normal Marshall or Hveem procedures (Takallou and Hicks, 1988). The PlusRide HMA is designed to modify the stability of a gap graded aggregate matrix with the elastic properties of CRA and a certain amount of binder modification. Conventional specimen preparation equipment and procedures are performed with some modifications, but the specimens are not tested for stability. The only measured specimen property used to establish the mix design asphalt content is percent air voids. The target air void content is

2 to 4 percent (Heitzman, 1992). The reported advantages of using the PlusRide in HMA applications are (PlusRide, 1984; reported by McQuillen and Hicks, 1987):

1) reflective and thermal pavement cracking is greatly reduced;
2) resistance to studded tire wear is increased;
3) skid resistance is increased;
4) ice removal by elastic deformation of the rubber granules under traffic loading and vehicle generated wind;
5) suppression of pavement tire noise; and
6) recycling of used rubber tires.

2.6.7 Discussion - CRA in Asphalt Paving Products

Various laboratory, field, and analytical studies (e.g., Esch, 1984; Lundy, et al., 1987; McQuillen, et al., 1988; Takallou and Hicks, 1988; Schnormeier, 1986; Takallou, et al., 1985; 1986; and 1989; and Vallerga, 1980) and industry publications (e.g., PlusRide, 1984; Arm-R-Shield, 1986) indicate that adding CRA to asphalt paving products (as a binder or as an aggregate) improves the engineering characteristics of pavements, including the service life. However, a careful analysis of information obtained as a result of the questionnaire survey (Ahmed, 1991) and scrutiny of the published literature indicated that these claims are not always substantiated by the field performance of asphalt paving products containing CRA. The experience in the use of CRA in asphalt paving products showed both successes and failures.

The experience of a number of states in the use of CRA in different categories of asphalt paving products was studied to establish the basic causes of observed failures. See Ahmed (1991) for the experiences of a number of states in the use of asphalt paving products. However, it appeared that, with a few exceptions, the failures and successes had been random and no definite reasons could be established for this unusual behavior (i.e., same percentage of CRA used in a similar product, under similar climatic environments demonstrated different behavior - one failed within a short time of construction, whereas, the other performed much better than the control sections). Various reasons have been offered for the inadequate performance of the products (e.g., NYSDOT, 1990; ODOT, 1990). The author is of the opinion that more research (analytical, laboratory, and field studies) is required to completely understand this technology.

It has been found (Ahmed, 1991) that asphalt paving products with CRA have also demonstrated consistently better performance in some states, e.g., Alaska (rubber modified asphalt) and Arizona (asphalt-rubber). Similarly, some of the asphalt paving products have displayed better performance in most of the cases and suffered fewer failures, which include two products that use asphalt-rubber binder, i.e., crack/joint sealant, and SAM.

Various studies on the economics of using CRA in asphalt paving products (e.g., KDOT, 1990; McQuillen et al., 1988; NYSDOT, 1990, Heitzman, 1992) show that the products are not cost effective, since the performance of the products is generally not commensurate with large increases in cost (the increase in cost, for all the categories, i.e., products from asphalt-rubber and rubber modified asphalt, is generally 50% to more than 100% higher than the conventional materials). However, the additional cost of asphalt-rubber as a joint/crack sealant is justified in view of better performance. Similarly, additional cost of materials used in SAMs has also been acceptable based on the life cycle cost in most of the cases, due to its somewhat better performance and generally longer service life.

The asphalt paving products containing CRA are generally acceptable from an environmental viewpoint. A recent study (Rinck and Napier, 1991) indicates that the risk to paving workers associated with its use are negligible. However, concerns are still expressed by some state highway agencies over increased air pollution and safety during blending, mixing, and laydown due to adding rubber to the mix and also the requirement of elevated temperatures during mixing.

The recycling of asphalt pavement has gained wide popularity due to obvious economic and environmental benefits. Research studies have generally not addressed this issue (limited studies have been performed, but conclusions can not be generalized, e.g., Charles, et al., 1980) in the case of asphalt-rubber or rubber modified asphalt. If these pavements cannot be recycled on completion of their service lives, the disposal of these pavements will create another major waste disposal problem.

2.6.8 Miscellaneous Uses of Crumb Rubber

Sound Attenuation - A property of ground scrap rubber which has not been fully exploited commercially is sound attenuation. The research conducted by the Firestone Tire & Rubber Co. has revealed that ground scrap rubber in various paints and coatings can significantly reduce sound transmission of substrates coated with the mixture. The products are directed for use in areas where noise is a problem (Beckman, et al., 1974).

Crumb Rubber in Concrete - Ground scrap rubber has been tried in Portland cement concrete. The product is of lower density than regular concrete and has both lower abrasion and lower compressive resistance. Cured rubber/concrete tends to pulverize rather than chip on impact and does not polish as easily as conventional concrete, but is more easily cut with a saw. Rubberized concrete could find its use in architectural applications where light weight and ease of fabrication are important (Beckman, et al., 1974)

2.7 Incineration/Co-firing

Scrap tires make an excellent fuel source with an estimated heating value ranging from 12,000 to 16,000 Btu/lb (EPA, 1991), with an average of 14,000 Btu/lb, compared to coal and municipal wastes fuel values of 12,000-12,600 Btu/lb and 2,500-8,500 Btu/lb, respectively (Beckman, et al., 1974). Scrap tires, in a well engineered and competently operated plant, can be blended with municipal waste or coal to improve their fuel value (heating value of a scrap tires and municipal waste mix approaches 10,000 Btu/lb). Proven technology exits to efficiently burn whole, shredded, or granulated tires, while meeting all applicable pollution control codes. However, size reduction of tires (i.e., shredding, chopping, splitting) and strict environmental laws may make tire combustion more expensive, due to substantial processing costs and requirement of sophisticated emission control devices, respectively.

Most of the plants currently burning tires for fuel do not have the capability to burn whole tires. Instead they must burn tires that have been shredded into small chips. In this form it is known as tire-derived fuel (tdf). The sizes of chips can vary from 2 to 6 inches, depending on the shredding operation and the user's requirements. Typically, the shredded tire chips also contain steel wires from the tire beads and steel belts. Removal of the steel wires involves an expensive process, requiring fine shredding and the use of powerful magnets, which makes tdf considerably more expensive. In 1990, about 25.9 million tires (10.7% of total generation) were burned for energy production. The use of tires and tdf in various combustion facilities is briefly discussed below (EPA, 1991):

1) Power plants - Waste tires utilization in tire burning plants has been mainly initiated by Oxford Energy, a company which is headquartered in Santa Rosa, California. The largest scrap tires combustion system is the Oxford Energy plant in Modesto, California, which consumes 4.9 million tires and generates 14 MW of power (EPA, 1991). A second Oxford Energy power plant, designed to burn about 9-10 million tires per year, is under construction in Connecticut. This plant, when completed, will be the largest tire combustion facility in world. In addition, the company has also announced plans to construct two more plants

capable of burning large quantities of scrap tires.

2) Tire manufacturing plants - Two Firestone tire plants have installed pulsating floor furnaces to dispose of scrap tires and other solid waste. These plants, located in Des Moines, Iowa, and Decatur, Illinois, were built in 1983 and 1984, respectively. Each of the incinerators has the capacity to burn 100 tons of waste per day, 25% of which is whole tires and scrap rubber. However, tires account for 80% of the Btus consumed by the furnaces. The Des Moines plant was shut down in 1987 for exceeding opacity limits. This plant burns large tires, which are difficult to burn without opacity problems. The plant requires addition of a baghouse, which is not economically feasible. However, no problem has been encountered in burning passenger tires in the Decatur plant (EPA, 1991).

3) Cement Kilns - Seven cement kilns in the United States utilize about 6 million scrap tires per year to replace conventional fuel. Cement kilns seem to be very suitable for scrap tires because of their high operating temperatures (2,600 °F) and good conditions for complete combustion, which minimize air pollution problems. In addition, there is no residue, since the ash is incorporated into the

cement product. Of the 240 cement kilns in the United States, about 50 are equipped with precalciner/preheaters, making them most suitable for tire combustion (EPA, 1991).

4) Pulp and paper plants - Many furnaces designed to burn wood chips at pulp and paper plants are suitable for burning tdf without major modifications. Frequently, only wire-free tdf can be used in these boilers, thus increasing the tire processing costs. An estimated 12 million tires per year are currently being consumed by the pulp and paper industry (EPA, 1991).

5) Small packages steam generators - There is currently only one small package generator operated in the United States, which is a Japanese system. The generator is operated by Les Schwab Tires, a retreader in Prineville, Oregon. The generator has been in operation since 1987 and uses 25 tires per hour. Another unit has been manufactured in Italy by Eneal Alternative Energy of Milan, which can burn 200 tire per hour and produce 22,000 pounds per hour of process stream (EPA, 1991).

Tire combustion facilities and the consumption of waste tires in the existing tires-to-energy plants indicate increasing trends. Whole tires may be incinerated directly or they can be shredded and incinerated as a fuel supplement. The factors which may make tire combustion cost effective include: less requirement of size reduction, as it eliminates the need for expensive processing; location of tire combustion facilities in geographic areas of high scrap tire density, to reduce handling and transportation costs; capability of plant to burn efficiently whole tires or tdf with least modifications to the existing facility to reduce initial costs; less stringent environmental laws, as the use of sophisticated emission control devices may increase initial and maintenance costs. Incineration of tires offers a solution to tire disposal problems. However, it may not always be economical to burn large quantities of tires in an environmentally acceptable manner.

2.8 Discussion

The various options used in the past, with varying degree of success, to reduce the scrap tire disposal problem are described in the preceding subsections. A scrutiny of these options suggests that no single option or process can solve the tire disposal problem. Various options need be tried simultaneously to overcome this problem. A careful review of available options, suggests that the available options broadly fall into five categories: 1) source reduction; 2) use of tires and their constituents in highway applications; 3) recycling tires into non-highway applications; 4) storage of shredded tires; and 5) combustion of tires and tire derived fuel (acronym tdf).

Source reduction can be achieved by taking a number of measures, including: improved maintenance of tires; design of longer wearing tires; reuse of used tires; and retreading. Under-inflation, severe braking, fast acceleration, and sharp turning may cause tires to wear out sooner than their usual service life. Conversely, proper maintenance and careful driving will increase their useful life. The development of radial tires has more than doubled tire life. At this point in time, a substantial increase in the tire life is not considered technically and commercially a viable option. However, reuse and retreading of tires is likely to significantly reduce the generation of scrap tires. Some of the measures to promote reuse/retreading of tires include: public education to produce better appreciation of the tire disposal problem, and to decrease their apprehensions/fears concerning poor quality/safety of retreaded tires; improving quality of retreaded tires; development of resource recovery systems; regulatory requirements; and economic incentives.

Various highway and non-highway applications of tires and their components are summarized in Figure 2.2. Among the various highway applications: use of CRA in asphalt pavements; shredded tires in embankments as lightweight fill;

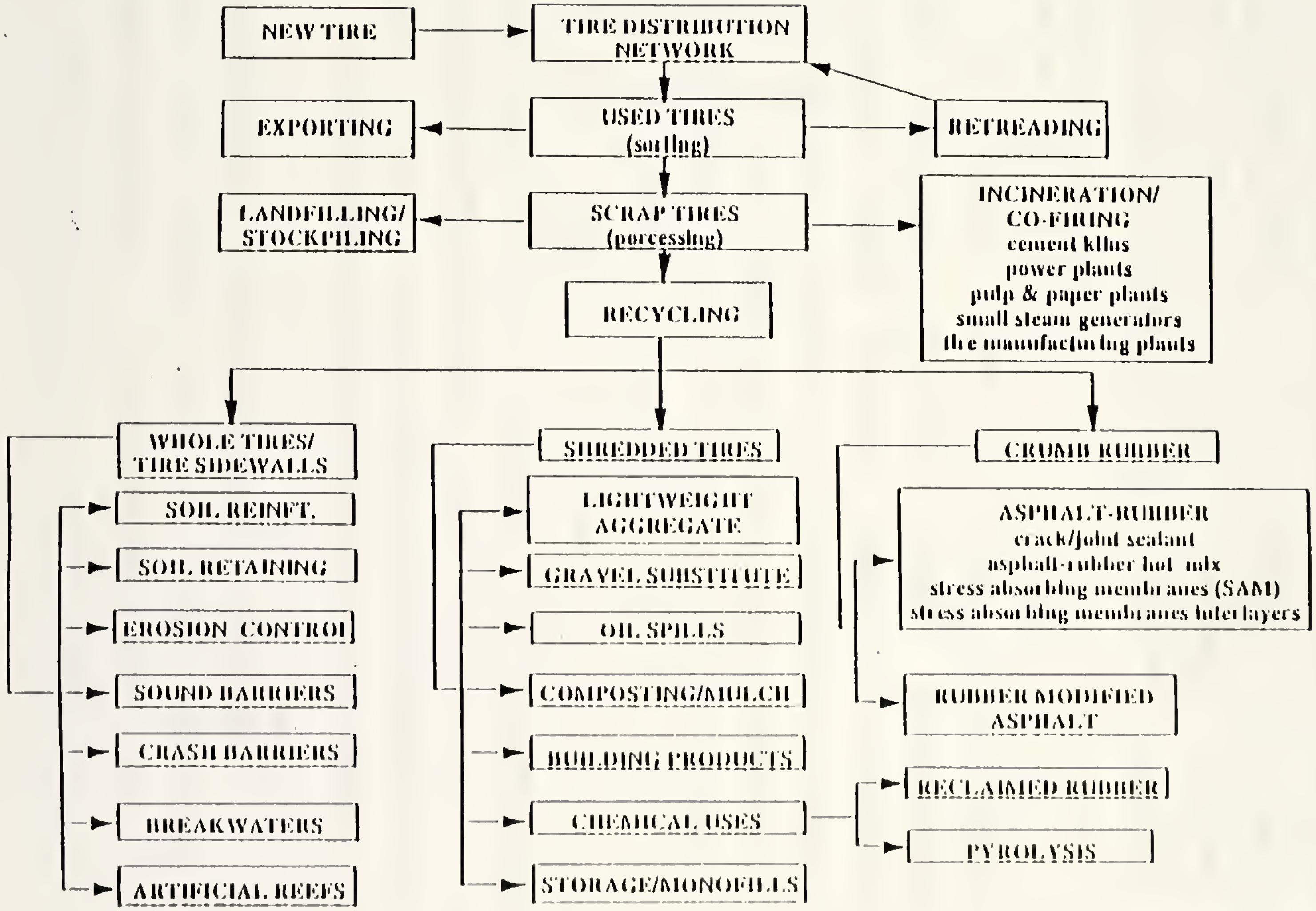


Figure 2.2 A summary of recycling and disposal options for scrap tires

and tires/components in subgrade/embankment for soil reinforcement hold significant promise for consuming large quantities of tires, with considerable engineering benefits. These applications were discussed in some detail in previous subsections. However, each of these applications has technical, economical, and environmental implications, which need to be addressed prior to its extensive use in highways.

The non-highway applications which can consume large quantities of tires and have potential for further development, include: breakwaters, artificial reefs, and reclaiming of rubber and other product through chemical reclaiming processes and pyrolysis. Although all these applications have been experimented with in the past, currently none of these applications is commercially viable. Although, the other applications included in Figure 2.1 (e.g., soil retaining, erosion control, sound barriers, building products) are not likely to expand substantially in the near future, they are contributing positively in solving the tire problem. Therefore, use of tires and its products in other applications should also be encouraged.

Stockpiling of tires in the open is unsightly, is a fire hazard, and creates a breeding ground for mosquitoes. It is not legal in most states. However, storage of shredded tires in covered installations or monofills, with adequate measures against any adverse impact on environments is a viable option, allowing conservation of this valuable material. Further technological advances can convert this material into a valuable product, or a rise in the cost of petroleum feedstock may make reclaiming and pyrolysis commercially viable processes. Storage of shredded tires, in an environmentally acceptable manner, may be preferred over combustion of tires.

Scrap tires, with heating value slightly higher than coal, make an excellent fuel source. Usually tires are shredded or chopped (generally called tdf) and then burned alone or mixed with coal. Of the currently available tire-to-energy facilities, power plants, cement kilns, and pulp and paper plants hold a greater promise to burn the tdf efficiently and in environmentally acceptable manner. However, it may be noted that tires are highly durable, lightweight, and have intrinsically high tensile strength. These properties make tires a useful engineering material. Burning of tires is considered a waste of natural resources and is not a beneficial use of scrap tires. This option may be resorted to sparingly and under the circumstances that no recycling option can be practically exercised.

2.9 Conclusions

This section summarizes the various options available to reduce the scrap tire disposal problem and also benefit from recycling of this highly durable engineering material (see Figure 2.2 for a summary of available options). Broadly, the various options include: the reduction of waste tire generation; reuse of chemically unaltered material, in whole tires or after processing; the reclaiming of rubber, constituent materials, or chemicals from scrap tires to recycle them in the manufacture of new products; and the recovery of heat value. Of all the options currently available for the disposal of scrap tires, no single option appears to be so outstanding which can significantly minimize the tire disposal problem, economically and also in an environmentally acceptable manner. Many options/processes need to be simultaneously tried and developed to solve the problem.

A careful review of the currently practiced tire reduction/recycling options/processes, led to the following salient conclusions:

1) Waste tires may be recognized as a valuable raw material. The factors which favor recycling and must be exploited, include: high physical durability, elastic in nature, intrinsically high tensile strength, lighter in weight, high heating value, low costs, and positive effect of recycling on environments. Factors which are impediments b

recycling and must be considered while exploring/trying various recycling processes, include: inherently complex chemical composition and manufacturing process, which makes them bulky, resilient, non-biodegradable, and potentially combustible; variability within the same type and also within different categories of tires; and questionable leachates under adverse environmental conditions.

2) Of the available options in source reduction (i.e., longer service life, reuse, and retreading), reuse and retreading are economically/commercially viable and environmentally desirable options. Retreading holds greater promise for significant reduction in the waste stream. An increasing trend in retreading truck, bus, construction/agriculture machinery, and aviation tires and a decreasing trend in automobile tires is observed. Reduction in scrap tire generation can be encouraged by various measures, including regulatory requirements and economic incentives.

3) Burying of whole tires is an environmentally undesirable option and a waste of natural resources, and should be discouraged either by law or by high disposal fee.

4) Processed scrap tires (cut, sliced, or shredded)

are easy to handle/transport and occupy smaller landfill space. Scrap tires which cannot be recycled currently may be stored in monofills or installations in such a manner that they have no adverse impacts on environments, until development of technology in the future that may convert scrap tires into a high value product.

5) The present technologies to reclaim rubber or separate tires into ingredients do not yield products that can compete, in terms of price or quality, with the similar products in the market. Further research is required to develop technologies for reclaiming high quality crumb rubber for reuse in manufacturing new tires and other rubber products.

6) The potential areas for recycling tires in highways are identified in Figure 2.2. Three applications of waste tires and their products hold significant potential for future projection: use of CRA in asphalt pavements; use of shredded tires as lightweight fill; and use of tires and its products for soil reinforcement. The use of asphalt-rubber as crack/joint sealants and SAMs may be further projected since the products have generally performed satisfactorily and are also found cost effective on a life cycle cost basis. Technical,

economic, and environmental issues concerning asphalt-rubber and rubber modified asphalt mixtures need to be addressed prior to their extensive use in the pavements (also see Kaya, 1992). The use of tires in subgrades/embankments has been tried in the field successfully and found beneficial as it can consume large quantities of locally available tires (Bosscher et al., 1992; Caltrans, 1986; 1988; Edil, et al., 1990; Lamb, 1992; Mn/DOT, 1990; MPCA, 1990, Read, 1991; and Read, et al., 1991). However, information concerning engineering properties, testing procedures, and design aspects of rubber-soils are severely lacking.

7) Non-highway applications which can potentially consume large quantities of waste tires are: breakwaters, artificial reefs, and reclaiming of rubber/other ingredients. A review of available technologies and markets suggest that these applications are not commercially beneficial at this point in time.

It is evident that the waste tire problem in the United States is of great magnitude and has far reaching environmental and economic implications. It is found, based on a critical analysis of the available options for reuse, recycling, and disposal of scrap tires that no single option can solve this problem. A comprehensive strategy is required to combat this problem at government, industry, and public levels. Federal, state and local officials need to integrate their efforts to muster support of the nation to solve this problem. A five point approach is recommended:

1) Develop and implement comprehensive laws governing manufacture, discards, disposal, storage, incineration, reuse, and recycling of tires.
2) Take measures to reduce the number of scrap tires generated (i.e., source reduction by having longer wearing tires, reuse, retreading) which may include: regulatory requirements, economic incentives, etc.
3) Promote use of scrap tires and their components in highway and non-highway applications which hold great promise for consuming large quantities of tires in an environmentally acceptable manner, at significant economic benefits. Three potential areas are identified in each sector for further projection: in highways - CRA in asphalt paving products, shredded tires as lightweight fill, and tires and its products for soil reinforcement; in non-highway applications - breakwaters, artificial reefs, and reclaiming products through chemical decomposition of tires.
4) Permit storage of processed tires (i.e., shredded,

sliced, or chopped) which cannot be recycled currently, in safe installations/monofills where they have no adverse environmental impacts, for use in the future when technological advances can convert processed tires into high value products.

5) Allow incineration of tires only in those tire-to-energy facilities which can burn tires or tdf efficiently, while complying with all the emission control regulations.

CHAPTER 3

SHREDDED TIRES AS LIGHTWEIGHT GEOMATERIAL

3.1 Introduction

Certain field and laboratory studies have indicated that there are many benefits to using tire chips as lightweight fill for embankments founded on soft, compressible foundations (Ahmed, 1992; Ahmed, 1993; Ahmed and Lovell, 1992b). Specifically, settlement is reduced and stability is increased. In addition, tire chips are non-biodegradable and are available in abundance, generally at no cost in the case of primary shreds at the source. Finally, use of tire chips as lightweight fill in highway structures can consume a large quantity of tires which will have a very positive impact on environments.

The inherent attractive engineering properties of tires have led to their use in a variety of engineering applications. This section synthesizes the information on the feasibility of using rubber tires as lightweight geomaterial in highway structures. The section contains: an overview of lightweight materials commonly used for highway embankment fills and other engineering structures; physical and chemical characteristics of tires; and salient aspects of field and laboratory studies in the use of shredded tires as a lightweight fill material. In addition, the section contains a brief discussion on performance, potential environmental impact and constructional aspects of shredded tire embankments. Finally, a summary of relevant conclusions is presented.

3.2 Conventional Lightweight Materials

Table 3.1 lists different types of lightweight materials and their salient properties. All have been used in the past, although some materials are more popular than others and some have been only used on an experimental basis or for structures other than highway embankments. The performance and cost differences between the various materials are significant. However, all have compacted densities significantly less than the unit weights of soils commonly used in embankment construction. Hence their use can substantially reduce the effective weight of embankment. A questionnaire survey by Holtz (1989) indicated that lightweight fill has been used to some extent by 40% of the United States highway agencies responding to the questionnaire.

Lightweight materials are usually expensive, especially

Table 3.1 Lightweight embankment fill materials (adapted from Holtz, 1989; Hartlen, 1985; OECD, 1979; Merdes, 1992; Elastizell, 1992; and other sources)

Material	Unit Weight (pcf)	Comments
Bark (Pine & Fir)	35-64	Waste material used relatively rarely as it is difficult to compact. The risk of leached water from the bark polluting groundwater can be reduced or eliminated by using material initially stored in water and then allowed to air dry for some months. The compacted/loose volume ratio is on the order of 50 percent. Long-term settlement of bark fill may amount to 10% of compacted thickness.
Sawdust (Pine & Fir)	50-64	Waste material usually used below permanent groundwater level but has occasionally been employed for embankments that have had the side slopes sealed by asphalt or geomembrane.
Peat: Air dried:		Proved particularly useful in Ireland for repairing existing roads by replacing gravel fills with baled peat.
milled	19-32	
Baled		
Horticultural	13	
Compressed Bales	51-64	
Fuel ash, slag, cinders, etc.	64-100	Waste materials such as pulverized fuel ash (PFA) are generally placed at least 0.3 m above maximum flood level. Such materials may have cementing properties producing a significant increase in safety factor with time. In some cases (e.g., furnace slag), the materials may absorb water with time, resulting in an increase in density.
Scrap cellular concrete	64	Significant volume decrease results when the material is compacted. Excessive compaction reduces the material to a powder.
Expanded Clay or shale (lightweight aggregate)	20-64	The physical properties of this material, such as density, resistance, and compressibility, are generally very good for use as a lightweight fill, although some variations may be produced by the different manufacturing processes. The material is relatively expensive but can prove economical in comparison with other techniques for constructing high standard roads. In case this material is used in embankments, a minimum of 20 in. depth of soil cover is required on the slopes and minimum thickness of road base is 2 ft.
Shell (oyster, clam, etc.	70	Commercially mined or dredged shells available mainly off Gulf and Atlantic coasts. Sizes 0.5 to 13 in. (12 to 75 mm). When loosely dumped, shells have a low density and high bearing capacity because of interlock (Mitchell, 1970).

Table 3.1, Continued

Expanded polystyrene	1.3-6	This is a superlight material used in Norway, Sweden, the United States, and Canada up to the present, but where its performance has proved very satisfactory and its usage is increasing. The thickness of the cover varies between 0.5 and 1 m, depending on traffic loading conditions. The material is very expensive, but the very low density may make it economical in certain circumstances.
Neutralysis	108-115	Neutralysis is a process that integrates materials recovery, waste conservation, and lightweight aggregate manufacturing. The manufacturing process combines non-recyclable solid and liquid wastes fraction of the total non-hazardous waste stream with clay or shale to produce a pelletized feed stock which is then pyro-processed in a series of rotary kilns in which the waste is utilized as fuel. Merdes (1992) reports that the process produces an inert, high quality, lightweight ceramic aggregate ready for use in structural concrete, masonry block manufacturing, and other applications for high quality lightweight aggregate. The aggregate meets ASTM compressive strength requirements (ASTM C330-87). The process is patented by Neutralysis Industries Development Company (NIDC) Northfield, Illinois. The company is currently planning to site a Neutralysis plant in Northwest Indiana and will sell the aggregate for $25 per ton at the plant (Merdes, 1992a).
Low-density cellular concrete, Elastizell: Class I Class II Class III Class IV Class V Class VI	 24 30 36 42 50 80	This is a lightweight fill material manufactured from portland cement, water, and a foaming agent with the trade name "Elastizell EF" and is produced by Elastizell Corporation of America, Ann Arbor, Michigan. Six different categories of engineered fill are produced, i.e., Class I to VI, which have compressive strength 10, 40, 80, 120, 160, and 300 pcf, respectively. Whereas ultimately bearing capacity of Class I-IV is reported as 0.7, 2.9, 5.8, 8.6, 11.5, and 21.6 tsf, respectively. The material is cast in situ and has been used as lightweight fills in a variety of geotechnical applications, such as highway embankments, bridge approaches, foundations, etc. (Elastizell, 1992).
Tire chips	20-45	Shredded tires as a lightweight material has been experimented with by a number of states. The benefits include: reduced weight of fill, a free draining medium; inexpensive; and recycling of tires. Potential problems include: leachate of metals and hydrocarbons; high compressibility; and fire risk. Recommended in unsaturated zones of embankment until long term environmental monitoring confirm no likelihood of adverse effects of leachates on groundwater. Need to have a soil cover on top and sideslopes for safety against fire and also provide adequate confinement. Settlements can be reduced by using a thick soil cap and rubber-soil mix instead of chips alone (Author).

if they are manufactured (e.g., expanded shales and clays, polystyrene, lightweight concrete, etc.). Typically, costs range from $50 up to $100 per cubic yard, including transportation (Holtz, 1989). Some waste materials (i.e., sawdust, bark, shells, cinders, slags and ashes, etc.) are almost free at the source and only need to be transported to the site. Thus their cost will depend on the distance between the source of waste material and the site. Lightweight fills have also been reportedly found cost effective alternatives in certain applications in the field of geotechnical engineering (Childs, et al., 1983).

Expanded shale lightweight aggregate has been used by the construction industry for many decades to produce lightweight structural concrete and lightweight concrete masonry units (Stoll and Holm, 1985). The aggregate is expanded by heating shale in a rotary kiln under carefully controlled conditions at high temperatures (2100°F). The expanded, vitrified mass that results from this process is then screened to produce the desired gradation for a particular application. NCHRP (1971) reported that some expanded shale has poor freezing resistance and must be kept dry.

Stoll and Holm, (1985) conducted large scale triaxial compression tests on specimens of lightweight expanded shales from five different locations in the United States and also performed uniaxial strain tests (consolidation tests) on aggregate from one of the sites. Their results indicated that the response under triaxial loading was similar to that of many ordinary coarse fill materials; the principal difference is that the lightweight aggregates weigh roughly half as much as conventional materials. Thus the lightweight aggregates may prove to be useful substitutes for ordinary fill materials when the combination of low weight and substantial shear strength warrant the increased cost. The mechanical properties of the aggregate tend to vary somewhat from source to source, so they should be verified in each instances. NCHRP (1971) states that expanded shale seems to be a favorite lightweight fill material because of its more certain behavior.

Nelson and Allen (1974) reported a successful landslide correction using bark and sawdust in a sidehill embankment. They used a 12 inch gravel base under the pavement section; in addition, an asphalt seal was placed on the exposed slope to retard deterioration and pollution. There have been many other projects that used sawdust and bark as lightweight fill in the Pacific Northwest. Large quantities of sawdust were used in the approach embankments to the Dumbarton Bridge in San Francisco (Holtz, 1989). Edil (1983) reported the use of sawdust, wood chips, and expanded shale in the lower portion of surcharge fills on peat. The lightweight part of the fill was left in place after the surcharge was removed.

Hardcastle and Howard (1991) reported the results of a laboratory study on properties of wood fibers used as lightweight fill in embankments for runways and aprons of Benewah County airport (located near St. Maries, Idaho). The various reported properties of wood fiber are: submerged, dry, and wet unit weights as 5, 14, and 55 pcf, respectively; and Φ at 5% and 20% strains as 10° and 30°, respectively. The measured settlement after 32 months of an 8 ft. embankment ranged from 0.07 to 0.53 ft, which was twice the predicted value. Cox (1985) reported the coefficient of compressibility for isotropic stress increases of 0.01 to 0.02 per psi for wood chips.

Expanded polystyrene (EPS) is considered a superlight material, because it is about 100 times lighter than ordinary fill materials (unit weight as low as 1.25 pcf; Frydenlund and Aaboe, 1988). The material is available in blocks and can be made sufficiently strong to be able to support ordinary highway pavement and traffic loads with tolerable settlements. But it is also an excellent insulator, and there has been some hesitancy among highway departments in the Northern United States to use it within 4 ft. of the pavement surface because of potential differential icing problems. Other problems with EPS include reports of burrowing animals in the material and increases in unit weight because of water absorption (Holtz, 1989).

Conversely, experience with EPS in a number of countries has been very positive. Frydenlund and Aaboe (1988) reports that more than 100 road projects involving the use of expanded polystyrene (EPS) have been successfully completed in Norway with volumes varying from a few hundred to several thousand cubic meters of EPS. Applications include embankments on soft and highly compressible soils, behind bridge abutments, construction of sidehill embankments on unstable slopes and for rapid construction of pedestrian underpasses. In Sweden, more than 20 road embankments have been constructed with EPS (Hartlen, 1985). To prevent the EPS from being dissolved by petrol or other chemicals in case of a spill from an overturned tanker on the road, a 4 to 6 in. reinforced concrete slab is cast on top of the EPS blocks. The concrete slab also contributes to the strength of the pavement structure and reduces the total thickness of pavement material above the EPS blocks. EPS does not decay. The material is not fire resistance, and needs to be properly encapsuled in soil/ concrete (Frydenlund and Aaboe, 1988).

3.3 Tire Characteristics

Although automobile and truck tires manufactured today are primarily steel-belted radial ply type, other types of tires are available. Some tires are made with fiberglass, Aramid, and/or Rayon. Table 3.2 lists different types of tires and their properties. Most modern tires have a complex composition of natural and synthetic rubbers, chemicals, minerals, and metals. Steel-belted radial ply tires may also contain polyester, steel, or nylon cords. Some radial tires have a fine carcass wire, whereas bias ply tires do not. Both radial and bias ply tires contain bead wire, which consists of numerous strands of high tensile strength steel. In the past, both automobile and truck ties have been either radial or bias ply type. Some bias ply tires are still manufactured in the United States, but they are primarily truck tires. About one-half of the truck tires present in the market today are radial and one-half are bias ply types (OAQDA, 1991).

The main constituents of rubber in tires are carbon and oil (hydrocarbons), hence the combustible nature of tires. When tires burn in uncontrolled environments, the black smoke that escapes contains fine particles of carbon. Carbon and hydrogen can make up as much as 96.5 percent of the tire. However, the percentage of ash can be as high as 25%, especially if rubber contains steel (Granger and Clark, 1991; reported by OAQDA, 1991). Although, tires contains a significant amount of sulfur, they are comparatively lower in

Table 3.2 Tire characteristics (after OAQDA, 1991)

TIRE TYPE	SOURCE	ENERGY CONTENT (BTU/LB)	COMPONENTS, PERCENT BY WEIGHT						
			MOISTURE	ASH	SULFUR	CARBON	HYDROGEN	NITROGEN	OXYGEN
FIBERGLASS	POPE, 1991	13,974	0.00	11.70	1.29	75.80	6.62	0.20	4.39
STEEL-BELTED	POPE, 1991	11,478	0.00	25.20	0.91	64.20	5.00	0.10	4.40
NYLON	POPE, 1991	14,908	0.00	7.20	1.51	78.90	6.97	< 0.10	5.42
POLYESTER	POPE, 1991	14,752	0.00	6.50	1.20	83.50	7.08	< 0.10	1.72
KEVLAR-BELTED	POPE, 1991	16,870	0.00	2.50	1.49	86.50	7.35	< 0.10	2.11
UNSPECIFIED TIRE	HALEY, 1984	16,146	0.00	1.50	1.80	89.20	7.30	0.20	NR
UNSPECIFIED TIRE	RYAN, 1989	15,550	0.50	5.70	1.20	83.20	7.10	0.30	2.50

NR - NOT REPORTED

sulfur than oil and U.S. coal (except low-sulfur coal). The ash resulting from burning coal or TDF (tire-derived fuel) contains metals. Zinc is the main constituent in TDF fly ash, but lead, arsenic, chromium, and cadmium are also present (Granger and Clark, 1991).

Ohio Edison Company conducted a testing program, in May 1990, to determine the feasibility of co-firing whole waste tires and pulverized coal in their plant in Toronto, Ohio (Gillen, 1991). They conducted three test runs daily for each of the five operating conditions, i.e., 0%, 5%, 10%, 15%, and 20% total BTU input to the boiler provided by tires. During five-day tire burn tests, three fly ash and one bottom ash samples were collected daily. The samples were analyzed by Wadsworth/Alert Laboratories, Incorporated, of North Canton for RCRA heavy metals using the USEPA Toxic Characteristic Leachate Procedure (TCLP). Gillen (1991) reported that all TCLP leachate results for fly ash from the tire burn test were below hazardous waste limits of 100 times the drinking water standards. In addition, all TCLP leachate results for fly ash from the tire burn test were below Ohio solid waste limits of 30 times the drinking water standards, while 72 of these 120 test results passed drinking water standards for heavy metals. For bottom ash from the tire burn test, all leachate results were below drinking water standards for heavy metals.

Rubber tires are designed to withstand the rigors of the environment so that they will have a reasonable useful life on vehicles. Therefore, it is not surprising that discarded tires persist for longer periods. Indeed, it has been estimated that a whole tire requires at least a hundred years to decompose fully (Hofmann, 1974; reported by Cadle and Williams, 1980). The US Army has performed extensive tests of filled rubber vulcanizates to determine the effects of environmental aging on their physical properties (Bergstrom, 1977). It has been reported that styrene-butadiene rubber, the major tire tread vulcanizate, required several years of environmental exposure to show measurable changes in tensile strength or elongation. However, polybutadiene rubber, also a tire-tread component, aged much faster.

Several factors, such as heat, oxygen, ozone, light, humidity, and microorganisms, effect the degradation process (Cadle and Williams, 1980). Selective studies have been made on some of these factors. Cadle and Williams (1980) have reported a study on the environmental degradation of tire-wear particles. They collected soil samples from the roadside. The samples contained different amounts of rubber particles worn from automobile tires. These samples were subjected to different environmental conditions and degradation processes to analyze the effects of various factors on the degradation of rubber particles. The conclusions of their study cannot be applied directly to the degradation of rubber chips used in engineering structures, e.g., embankments, slides areas, etc., where they are not exposed to direct sunlight or other adverse environmental conditions. However, it can be inferred that the protection of rubber chips from severe environmental conditions will further reduce the very slow rate of their degradation.

3.4 Field Performance of Tire Chips in Minnesota

Various agencies, in the United States and abroad, have evaluated the use of shredded tires as a lightweight material in embankment construction and also for enhancing the stability of slopes in slide areas. The Minnesota Pollution Control Agency (MPCA) has documented over 23 sites (through April, 1992) throughout the state which have used over 80,000 cubic yard of shredded tires (about 2.2 million tires). Over half of these projects are privately owned driveways and roads, 4 are city and township roads, 3 are county roads, and 2 are DNR Forest roads. A few of the projects used shredded tires for purposes other than in road fills. One project in downtown Minneapolis used the lightweight tire shreds as a fill material to support a park and landscaping above an underground parking lot. At another site, tire chips were used as lightweight fill over an existing water main (Lamb, 1992). Six case studies (documented by the Minnesota DOT in a recent report) are described in succeeding sub-sections (location and cross sections are given in Figures 3.1 and 3.2, respectively), portions of which are excerpted from Lamb (1992).

3.4.1 Case Study 1: Ramsey County, Minnesota

A stretch of roadway on Ramsey County Road 59 (near St. Paul, Minnesota), which passes over a mucky low lying area with high water table, experienced excessive settlements and in 1990 required reconstruction. An economic and engineering analysis, conducted by TKDA (a consulting engineering firm) and Twin City Testing Corporation (the geotechnical subconsultant), resulted in the selection of shredded waste tires as the design fill material.

The construction commenced in the winter of 1990. The existing material was excavated to a depth of five feet. A geotextile fabric was placed at the bottom and sides of the excavation. Next, wood chips were deposited to a depth of one foot above the water table. About 4,725 cubic yards of shredded tires were then placed on top of wood chips and compacted to a depth of three feet above the original roadway elevation. The 3x3 inch tire shreds were compacted with a dozer. The top layer of geotextiles fabric was then added and sewn to the initial layer of fabric in order to encapsulate the wood chips and tires. A 3 foot layer of granular material, 6-inch base layer, and 5.5 inches of

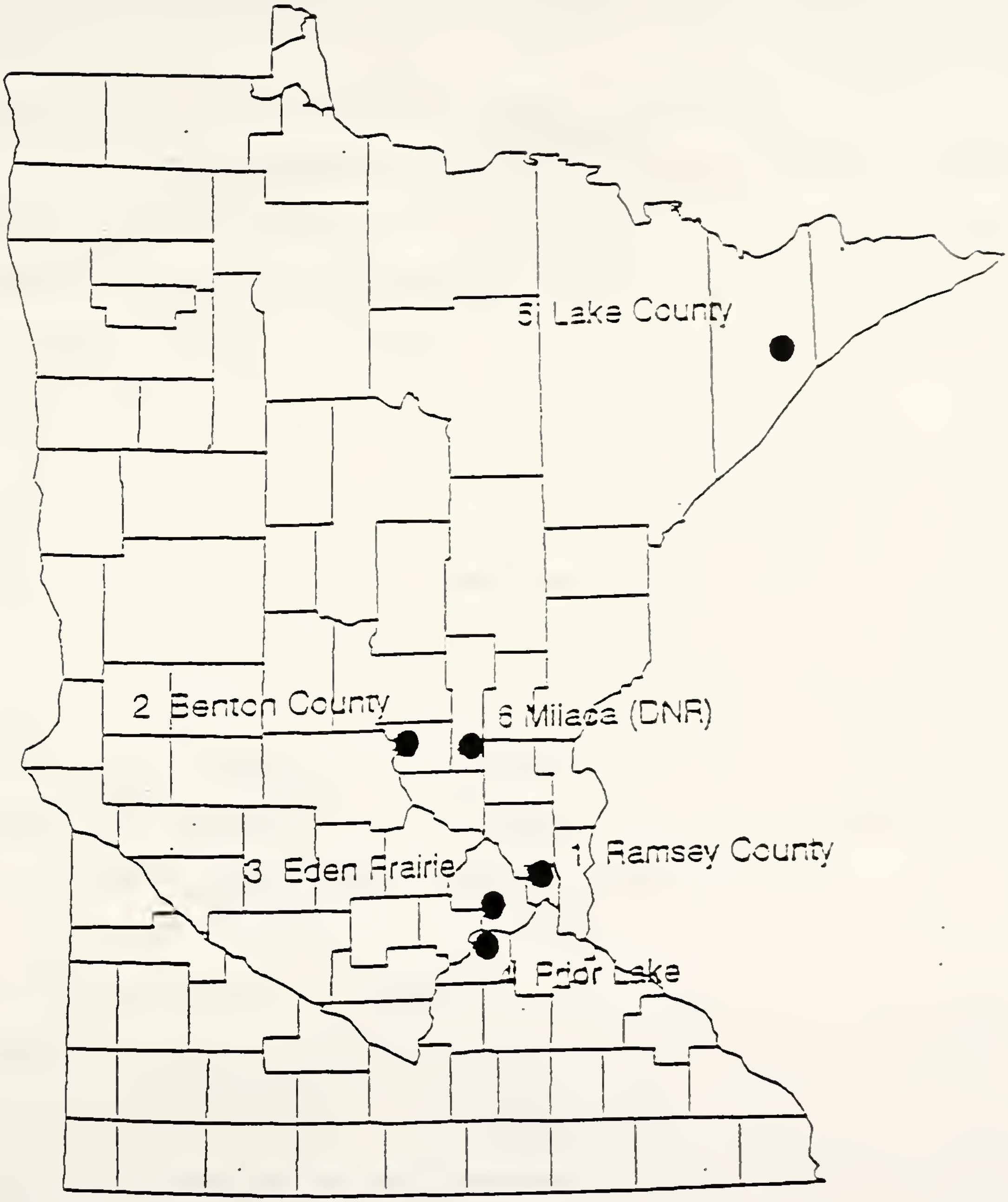


Figure 3.1 Location of case studies (from Lamb, 1992)

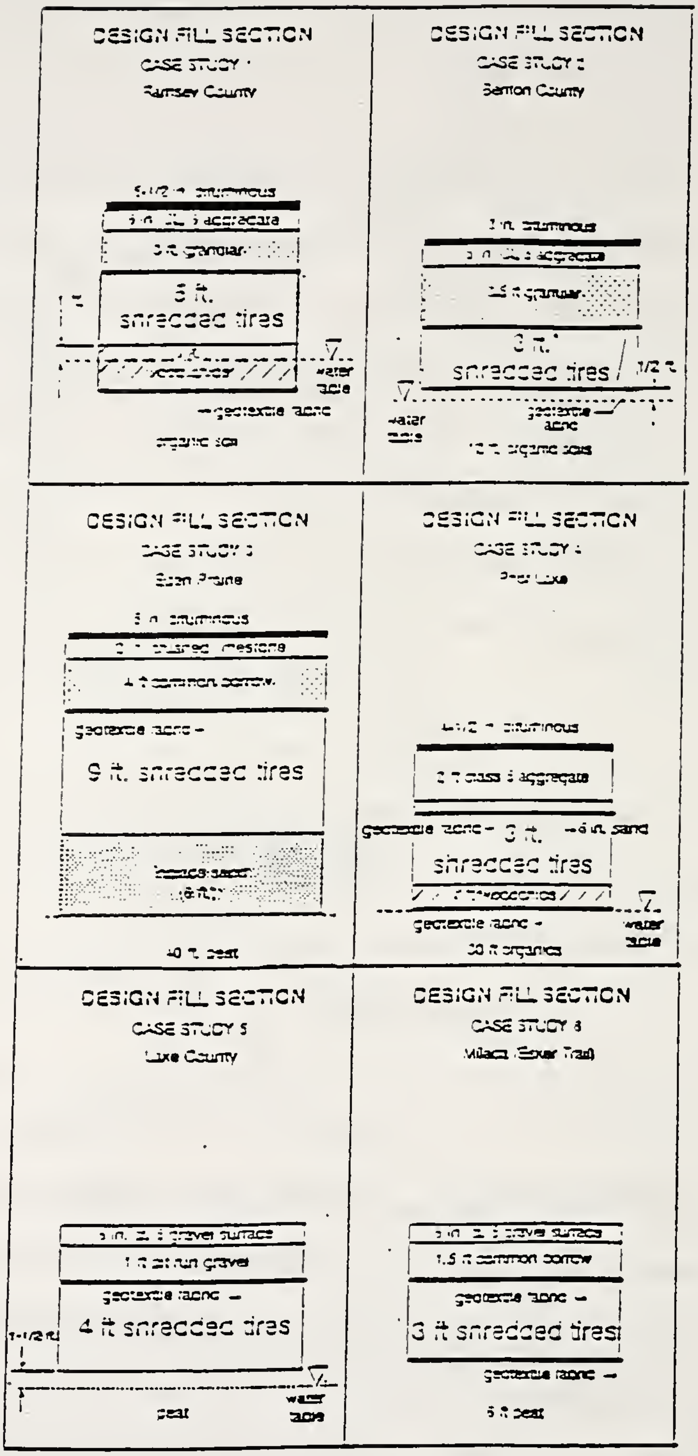


Figure 3.2 Cross-sections of case studies (from Lamb,1992)

bituminous base and wearing course were placed on a shredded tire fill (see Figure 3.2). The post-construction performance has not yet been reported (Lamb, 1992).

3.4.2 Case Study 2: Benton County, Minnesota

In this case, scrap shredded tires were used as roadway fill across a swamp that is underlain with peat and muck (Mn/DOT, 1990; and Public Works, 1990). The fill is located on County State Aid Highway 21 north of Rice, Minnesota, which is in the north-west corner of Benton County. The original construction across the swamp was stable, but subsequent additions to raise the roadway above the rising water in the swamp overloaded the underlying peat and muck and caused an embankment failure. The county hired a consultant (Braun Engineering Testing) to review options to correct the soil stability problem. After performing a cost/benefit analysis, it was recommended that shredded tires be used as a lightweight fill material.

The construction began in fall of 1989. The county excavated the embankment at the distressed portion, installed a geofabric, and then placed shredded tires directly on the fabric in 2-foot lifts to a height within 3.5 feet of the top of subgrade elevation. After the tire shreds were compacted, an additional layer of fabric was installed on top of the tires, prior to placing granular backfill. The tire fill supports: about 3.5 feet of clean granular soil cap, a conventional gravel subbase and base, and bituminous surfacing. The compacted shredded tire density is reported as 550 lb/cu yard. About 52,000 tires were used in the 250 foot portion of distressed roadway. Some of the construction specifications included (Public Works, 1990):

1) The largest allowable piece was about 8 inch square or round, and the longest piece allowed was 12 inch long, whichever was less.
2) It was required that chips be free from any contaminants such as oil, grease, etc., that could leach into groundwater.
3) Metal fragments were required to be firmly attached and 98% embedded in the tire sections.
4) All pieces must have at least one sidewall severed from the face of the tire.

To date (December 3, 1992), this road has not experienced any significant settlements and the bituminous surface is performing satisfactorily (Lamb, 1992).

3.4.3 Case Study 3: Eden Prairie, Minnesota

In Eden Prairie, Minnesota (near Minneapolis) a road embankment project incorporated shredded tires in order to solve a settlement problem (Lamb, 1992). The original fill, placed over a swamp containing 40 ft. of soft organic soils, failed during construction. Three years after the fill, the roadbed was still settling an average of one foot per year. It was decided to use shredded tires as lightweight fill to correct subsidence problem. The original fill was excavated to a depth of 10-14 ft and about 4,100 cu yards of shredded tires were then placed in 2-3 ft lifts. The tire shreds were 6-8 inches wide and 12-24 inches long and were compacted by a D-8 dozer to a density of 40-45 pcf. A geotextile fabric was placed on top of the tire shreds and 4 ft layer of common borrow was then placed on the fabric. After 3 weeks, 12 inches of crushed limestone was graded over the fill material followed by 3.5 inches of bituminous base course. The wearing course was paved the ensuing spring.

Settlement data, obtained from the settlement plates placed both at the bottom and top of the shredded tires, indicate that the fill has performed very well. Over a period of 19 months, the roadway settled an average of 0.9 inches a year, while the subcut (at the bottom of the tires) settled only an average of 0.4 inches per year (Lamb, 1992).

3.4.4 Case Study 4: Prior Lake, Minnesota

In Prior Lake, Minnesota (suburb of Minneapolis) the new alignment of the intersection of Duluth and Tower Avenues passed over a wetland area with 30 ft. of organic deposits. After analyzing various construction options, it was found beneficial to use shredded tires as a lightweight fill material. A geotextile fabric was placed over the wetland and then wood chips were compacted to an elevation of one foot above the expected water table level. Approximately three ft of shredded tires (about 9.600 cubic yards) were then graded over the wood chips. The 4 inch tire shreds were easily graded and compacted with dozers and loaders. The tire fill was covered with a 3 ft. of granular fill and base layer. A plate load test (applied directly on top of the shredded tires) indicated that the tire material was very compressible and displayed a very low modulus (Lamb, 1992).

3.4.5 Case Study 5: Lake County, Minnesota

The Lake County Highway Department reconstructed a gravel road using about 3,900 cubic yards of shredded tires on County State Aid Highway #7, near Finland, Minnesota. The original section, built over peat, experienced excessive settlements. After considering the various options, the county decided to construct the road using shredded tires as lightweight fill material. The road was constructed over the existing grade with a 4 ft layer of shredded tires, capped with a layer of geotextile fabric, followed by about 1.5 ft of gravel. The tire shreds were quite large, ranging in size from 4x12 in. to 1/4 th of a whole tire, and were compacted with a dozer. After two years, the county reports no noticeable settlement of the road section containing tires chips (Lamb, 1992).

3.4.6 Case Study 6: Milaca, Minnesota

The Minnesota Department of Natural Resources reported the use of shredded tires as lightweight fill on a 200 ft section of gravel road. The road, known as Esker Trail, passed over a section of wetland containing unstable peaty soil. The fill section included a layer of geotextile fabric, followed by 3 ft layer (3,000 cubic yards) of shredded tires, and then topped with a second layer of geotextile fabric. This was followed by 1.5 ft of common borrow, and capped with six inches of gravel. It has been reported that post-construction settlements were 40 to 50% less than were expected from mineral fill (Lamb, 1992).

3.5 Oregon Slide Correction Project

Based on successful experience of the Minnesota DOT in the use of shredded tires as a lightweight fill in embankment on weak foundation soil, the Oregon DOT also used shredded tires in a slide area on Highway U.S. 42 (Oregon State Route #35, Coos Bay-Roseburg), approximately 25 miles west of Roseburg, Oregon. The slide occurred in a newly-constructed 15 feet high embankment, with a slide block extending 150 feet beyond the toe of the embankment to a small creek running parallel to the highway. Succeeding paragraphs of this subsection describe the design, construction, and performance aspects of slide correction at this site by the Oregon DOT, portions of which have been excerpted from Read (1991) and Read, et al. (1991).

Geotechnical analysis suggested reduction of embankment weight and construction of a counterbalance berm between the embankment toe and the creek. The design called for replacement of the existing fill with shredded tires to reduce the weight of embankment. The actual construction involved replacement of 12,800 cu yard of existing soil with 5,800 tons of shredded tires (an estimated 580,000 tires). A drainage blanket consisting of 12 inches of free-draining rock between two layers of geotextile was placed beneath the shredded tire embankment and the berm in order to prevent the groundwater table from rising into the embankment. Three 10-foot-deep French drains were located beneath the blanket to enhance the subsurface drainage. The drainage blanket was required to prevent submergence of tire chips in water.

The embankment construction was completed in two stages to allow traffic on one half of the embankment while the other half was under construction. The shredded tires were brought to the project area from four different vendors, located 150 to 250 miles from the project, using 28 tons "live-bottom" trailers. Dump trucks were employed to deliver the chips to the construction site. A D-8 Dozer was used to spread and compact the chips. The shredded tires were placed in 2-3 ft lifts and each lift was compacted with no less than three coverage in each direction of a D-8 Dozer, achieving in-place density of 45 pcf. The reported density range of loose chips in the haul trailers varied from 24 to 33 pcf, depending on the haulage distance and size of the chips. Post construction density under 3 feet of soil, 23 inches of aggregate base, and 6 inches of asphalt and after 3 months under traffic (average daily traffic, ADT, of 3750 with 20% trucks) was 52 pcf.

The shredded tire fill was constructed to an elevation 12 inch above the design height to compensate for a 10% anticipated compression (the settlement estimates were based on in-situ performance of a tire chips embankment constructed in Minnesota; see Geisler, et al., 1989). It was observed that the thickest portion of the shredded-tire fill (approximately 12.5 feet) compressed 13.4% during construction as follows:

1) 16 inches during placement of 3 feet of soil cap.
2) 2 inches during placement of 23 inches of aggregate base.
3) 2 inches during 3 months of traffic and placement of 6 inches of asphalt concrete.

Deflection testing was conducted using ODOT's Falling

Weight Deflectometer (FWD). The average deflection of the pavement over the rubber tire fill was approximately 0.020 inch compared to a typical deflection of 0.010 inch normally measured for a similar asphalt- and -aggregate-base pavement constructed over a conventional soil subgrade. It is expected that, since the increase in dynamic deflection is apparently due to a deep layer (the tires), the deflection increase may have a larger radius and cause less stress in the pavement than similar magnitudes of dynamic deflection with conventional embankment underlying the pavement. The pavement has been heavily instrumented with slope inclinometers, settlement plates, and survey monuments. These devices are reportedly being monitored at regular intervals to determine the performance of the embankment, and the results are expected to be published in the final report.

Read et al. (1991) concluded that embankment construction using waste shredded chips is a viable technology and can consume large quantities of discarded tires at significant engineering benefits. The economics of using shredded tires in embankment depends on many factors, which vary with the local conditions, including: availability of other lightweight materials and their cost; proximately of site to the tire dumps and shredding equipment; and the existence of a state rebate program.

3.6 Use of Tire Chips to Cross Boggy Area

The Southeast Chester Refuse Authority in Pennsylvania was confronted with a problem of road construction over soft soil for movement of equipment from landfill to the storage sheds (Biocycle, 1989). They placed an 18 inch layer of tire chips (2x2 inch) along a 525 feet section of roadway passing over a boggy area, without compaction or any other treatment. It has been reported that the section containing tire chips drains well and provides a good riding surface.

3.7 Test Embankment Containing Shredded Tires

The University of Wisconsin-Madison, in cooperation with the Wisconsin DOT, has conducted a limited field experiment to determine the feasibility of incorporating shredded tires in highway embankment (Edil et al., 1990 and Bosscher, et al., 1992). They constructed a 16 feet wide and 6 feet high test embankment consisting of ten different sections, each 20 feet long, using locally available soil and shredded tires in a number of different ways, including: pure tire chips, tire chips mixed with soil, and tire chips layered with soil. They also varied the embankment configuration for different sections of embankment to determine the optimum slope. A geotextile fabric was placed on all sides of tire chips to serve as a separator between materials of the embankment and the surrounding materials. The embankment was constructed parallel to the access road of a sanitary landfill and exposed to the heavy incoming truck traffic.

The compaction was done using a sheepsfoot roller with vibratory capability. The field observation during construction included (Edil, et al., 1990):

1) The handling and placement of tire chips were not a problem. A back hoe was found appropriate for spreading the material evenly.
2) Tracked equipment could easily maneuver on tire chips.
3) Neither vibratory nor static compaction significantly induced compaction in the tire chips. However, non-vibratory compaction was found more appropriate.
4) The compacted field density varied from 20 to 35 lb/cu ft, depending upon type/size of chips.

Edil, et al. (1990), based on construction and initial post construction evaluations, have reported that construction of embankments using tire chips does not present any unusual problems. Leachate characteristics indicated little or no likelihood that shredded tires would effect groundwater. The main problem is reportedly related to control of compressibility. A two-year monitoring and evaluations of the test embankment supports the use of properly confined tire chips as a lightweight fill in highway applications (Bosscher, et al., 1992). Some of the observations include:

1) After an initial adjustment period, the overall road performance was similar to most gravel roads.
2) The embankment sections having 3 of feet soil cap performed better than that having 1 foot of soil.
3) The mixture of soil and chips performed similar to the pure chip sections with a thicker soil cap. The presence of a thick soil cap reportedly helps reduce plastic deformation.
4) Comparatively, the layered section performed the worst.
5) The leachate analysis indicated that shredded automobile tires show no likelihood of having adverse effects on groundwater quality.

3.8 Use of Tire Chips on a New Interstate in Colorado

The Colorado Department of Transportation has recently experimented with the use of shredded tires as a lightweight fill material (Lamb, 1992). Shredded tires have been used on a 200 ft portion of Colorado's new Interstate 76, a four-lane highway that will connect west Denver to Nebraska when completed in 1993. More than 400,000 tires chips of about four-inch size have been consumed in a 5 ft fill. The tire embankment has been instrumented for monitoring the long term performance of the fill.

3.9 Proposed Test Embankment in North Carolina

The North Carolina Department of Transportation (NCDOT) has initiated a project, with the assistance of the Federal Highway Administration (FHWA), to determine feasible usage of recyclable materials for highway construction (Whitmill, 1991). The project consists of widening a two-lane segment of NC 54 in Orange County to a four-lane divided highway for a distance of 2.182 miles. As part of this project, an embankment will be constructed with layers of shredded tires mixed with soil, using approximately 65,000 tires. The proposed embankment design requires:

1) Shredded tires may not be placed within three feet of the outside limits of embankment, within four feet of subgrade, or below the water level of the surrounding area.
2) The embankment shall be constructed by placing alternate layers of shredded tires and soil and mixing and blending them together during compaction.
3) Shredded tires shall constitute between 10% and 40% by volume of that portion of the embankment, achieving an average of 25 percent.

3.10 Laboratory Studies

Various databases, including: Compendex Plus (online form of engineering index); NTIS (National Technical

Information Service); TRIS (Transportation Research Information System); Enviroline; and Pollution Abstracts, were searched to locate the literature on the subject. Four laboratory studies were identified: 1) a limited laboratory study conducted by the University of Wisconsin-Madison to determine the mechanical properties of rubber and rubber-till mix, and leachate analysis of specimens collected from shredded tires test embankment (Edil, et al., 1990 and Bosscher, et al., 1992); 2) the Minnesota laboratory study on leachates from tire and asphalt materials (MPCA, 1990); laboratory study by University of Maine to determine the properties of tire chips for lightweight fill (Humphrey, et al. 1992 and 1993); and Caltrans study to determine permeability of tire chips (Bressette, 1984). All the studies are briefly described in succeeding paragraphs.

3.10.1 Wisconsin Study

A limited experimental program was carried out at the University of Wisconsin-Madison to develop quantitative information about the compaction and compression behavior of tire chips, and analysis of leachates from a test embankment made of rubber-soil (Edil, et al., 1990). Their experiment involved placement of rubber chips of different sizes alone and mixed with sand in a 6-in. Proctor mold and then applying load using a disk placed on the tire chips. The load-deformation response of rubber chips indicated that the major compression occurs in the first cycle. A portion of this compression is irrecoverable; but there is significant rebound upon unloading. The subsequent cycles tend to be similar with less rebound; however, the rebound is nearly the same from one cycle to another. It is observed that the slope of the recompression/rebound curve is markedly lower beyond a certain vertical load of about 1000 lbs.

Edil, et al. (1990) also conducted some compression tests on rubber-sand mix, varying sand/chip ratios. Their tests on rubber-sand mix yielded compression curves similar to rubber chips alone. However, the maximum compression increased as more and more cycles of loading took place, and the magnitude of the maximum compression was less than about 0.1 inch as compared to about 2 inches for the plain tire chips. Their test results, on specimens of sand/chip ratios varying from 100% sand to 100% chips, indicated that the compression increases significantly when tire chips content were increased beyond 30% by weight of sand.

The writer urges caution in using data reported by Edil, et al. (1990) concerning chips and chip-sand mix, since they conducted tests in a compression mold too small in diameter for the size of chips tested (chip sizes of 1.5 inch and even larger were tested in 6 inch Proctor mold). It is likely that greater side frictions are induced in a compression mold incompatible with the sizes of chips tested, which may have led to measuring incorrect load-deformation response. A careful review of reported data indicates that the reported deformations are significantly lower than are expected under corresponding loads.

Edil et al. (1990) have also reported duplicate EP toxicity and AFS leaching tests performed on tire chip samples by the Wisconsin State Laboratory of Hygiene. The test results indicate that the shredded automobile tire samples show no likelihood of being a hazardous waste. The shredded tires appear to release no base-neutral regulated organics. The tire samples showed detectable, but very low release patterns for all substances and a declining concentrations with continued leaching for most substances. It is suspected that several of these substances may have been released from surface coatings rather than leached from the tire material. Four metallic elements, i.e., barium, ferrous, magnesium, and zinc, exhibited increasing concentrations with continued leaching. The highest concentrations for Fe and Mn were at or above their applicable drinking water standards, while those for Ba and Zn were well below their standards.

Edil et al. (1990) report that by comparison to other wastes for which leach test and environmental monitoring data are available, the tire leach data indicate little or no likelihood of shredded tires effecting groundwater. Bosscher, et al. (1992) have reported that an overall review of the available leach data and results of the recent leach tests on samples collected from two lysimeters, installed during construction of the test embankment in December 1989, support their initial conclusions concerning potential impact of shredded tires embankment on environments, reported by Edil, et al. (1990). Their (Bosscher, et al., 1992) recent evaluations confirm that shredded automobile tires show no likelihood of having adverse effects on groundwater quality.

3.10.2 Minnesota Study on Tire Leachates

The Minnesota Pollution Control Agency (MPCA) sponsored a study on the feasibility of using "Waste Tires in Subgrade Road Beds" (MPCA, 1990). Twin City Testing Corporation (TCT) of St. Paul, Minnesota, performed the laboratory study to evaluate the compounds which are produced by the exposure of tires to different leachate environments. They subjected the samples of old tires, new tires, and asphalt to laboratory leachate procedures at different conditions, i.e., at pH 3.5, pH 5.0, approximately neutral pH and 0.9% sodium chloride solution, and pH 8.0. They also conducted field sampling. As a result of elaborate testing and analysis, TCT reached the following conclusions (MPCA, 1990):

1) Metals are leached from tire materials in the

highest concentrations under acid conditions; constituents of concern are barium, cadmium, chromium, lead, selenium, and zinc.

2) Polynuclear Aromatic Hydrocarbons (PAHs) and Total Petroleum Hydrocarbons are leached from tire materials in the highest concentrations under basic conditions.
3) Asphalt may leach higher concentrations of contaminants of concern than tire materials under the same conditions (see Table 3.3).
4) Drinking Water Recommended Allowable Limits (RALs) may be exceeded under "worst-case" conditions for certain parameters.
5) Co-disposal limits, EP Toxicity limits, and TCLP criteria are generally not exceeded for the parameters of concern.
6) Potential environmental impacts from the use of waste tires can be minimized by placement of tire materials only in the unsaturated zone of the subgrade.

3.10.3 Properties of Tire Chips for Lightweight Fill

Humphrey, et al. (1992 and 1993) have reported the engineering properties of 3-inch size tire chips from three suppliers. Their tests showed that the tire chips are composed of uniformly graded gravel sized particles that

Table 3.3 Comparison of asphalt and tires in leachate tests (MPCA, 1990)

Asphalt > Tires	Tires > Asphalt
Aluminum	As (detected @ pH 5.0 only)
Barium	Cd (detected @ pH 3.5 & 5.0)
Calcium	Cr (detected @pH 3.5 only)
Magnesium	Pb (detected @ pH 3.5 only)
Sulphur	Zinc
Selenium (@ pH 3.5 only)	Carcinogenic PAHs
Sn	-
Total petroleum hydrocarbons	-
Non-carcinogenic PAHs	-

absorb only a small amount of water. Their compacted density is 38.6 to 40.1 pcf. The shear strength was measured in a large scale direct shear apparatus. The reported friction angle and cohesion intercept ranged from 19° to 25° and 1.11 to 1.67 psi, respectively. Their compressibility tests showed that tire chips are highly compressible on initial loading but that the compressibility on subsequent loading/unloading cycles is less. The measured horizontal stress indicated that the coefficient of lateral earth pressure at rest varied from 0.26 for tire chips with a large amount of steel belt exposed at the cut edges to 0.47 for tire chips obtained from glass belted tires. In subsequent chapters, the reported data from their laboratory testing are compared with the results from the tests on tires chips conducted by the author.

3.10.4 Tires Chips as Aggregate in Drainage Layers

A laboratory study was conducted by Bressette (1984) to determine feasibility of using tire chips as an alternate to conventional aggregate in drainage layers/channels. He performed constant head permeability tests on compacted and uncompacted specimens of chopped used tire material (approximately 2-inch squares), shredded tires (100% passing 2-inch sieve), and coarse aggregate (open graded, percent passing sieves 2, 1.5, 1, 3/4, and 1/2 in. was 100, 99, 43, 39, and 1%, respectively). The permeability values for the three materials were within the same order of magnitude, i.e., 10^4 ft/day (with only 3 exceptions in 42 tests). All values were in the upper range of permeability values required for subdrainage material. Although the tire chips were found technically feasible as an alternate permeable material, the trends in the availability of used tires by-products in California, at that point in time, did not favor the use of tire chips as a substitute material in a permeable layer/drainage channel.

3.11 Discussion

The preceding subsections present a summary of commonly used lightweight materials, physical and chemical characteristics of tires, and various laboratory and field studies on shredded tires. A review of commonly used lightweight materials (Subsection 3.2 and Table 3.1) indicates significant diversity in their engineering properties. They also widely differ in their relative cost and for their impact on environments. Hence, dry density or any other property alone cannot be a sole criterion for comparison of different lightweight materials. Some materials, especially manufactured, possess very attractive engineering properties, but they also cost more. In certain cases some manufactured materials are not available in the large quantities required for highway construction purposes.

Lightweight waste materials, such as sawdust, bark, slags, cinders, and ashes, are generally available in abundance and mostly at no cost at the source. These materials have traditionally been used as lightweight fills by the United States highway agencies and may be rationally compared with another waste, like tire chips. Sawdust and bark have unit weights ranging from 35 to 64 pcf, are biodegradable, difficult to compact, require treatment to prevent groundwater pollution, need to be encapsuled in soil cover, and undergo significant long term settlement (see Table 3.1). Salient properties of slags, cinders, and ashes include: dry unit weights ranging from 64 to 100 pcf; may absorb water, resulting in an increase in density; possess high variability; and leachates may adversely effect groundwater quality or the structures in the vicinity of waste material (Table 3.1; Ahmed, 1991; Huang, 1990).

Rubber tires by the millions are discarded annually in the United States and tire chips are available in abundance. Tires possess high tensile strength, are chemically very stable and practically non-destructible. Field density of shredded tires varies from 20 to 45 pcf, depending on the size of chips, method of compaction, and thickness of compacted layers. No unusual problems have been encountered during field compaction of tire chips. A back hoe is considered suitable for spreading the chips. A D-8 crawler tractor is found appropriate for compaction. The environmental impact studies indicate that shredded tires are not a hazardous material, as the parameters of concern do not generally exceed the EP Toxicity and TCLP criteria (MPCA, 1990; Edil, et al., 1991; and Bosscher, et al. 1992). However, the Drinking water Recommended Allowable Limits for Minnesota are exceeded under "worst case" conditions (MPCA, 1990).

To minimize the potential adverse effects of leachates from tire chips, MPCA (1990) recommended the use of tire chips only in unsaturated zones. Note that the various parameters of concern leached from the tire chips depend on the environmental conditions prevalent in embankment fill, i.e., pH of permeant and soil. Hence, the worst conditions upon which the conclusions have been based (i.e., extreme pH values) may not exist in a shredded tire embankment. This is confirmed by a recent report by Bosscher et al. (1992), which is based on two-year environmental monitoring and evaluation of leachates from a test embankment incorporating shredded tires. The report states that "...by comparison to other wastes for which test and environmental monitoring data are available, the tire leach data indicate little or no likelihood of shredded tires having adverse effects on groundwater."

A major concern in using tire chips in embankment is the large settlements (about 10 to 15%) observed in various field and laboratory studies (e.g., Geisler, et al., 1989; Edil, et al., 1990; Lamb, 1992; and Read, et al., 1991). Holtz (1989) comments that no research has been reported in the literature on tolerable settlements of highway embankments. NCHRP (1971) has reported that post-construction settlements during the economic life of a roadway of as much as 1 to 2 ft are generally considered tolerable provided they: 1) are reasonable uniform; 2) do not occur adjacent to a pile-supported structure; and 3) occur slowly over a long period of time. Post-construction settlements of shredded tire embankments can be reduced by: placing a thick soil cap over tires fills, i.e., by increasing confining pressure; and using a rubber-soil mix instead of tire chips alone. The detrimental effects of anticipated excessive settlements can be reduced by using tires under flexible pavements only and letting the tire chips compress under traffic before placing the final surface course.

Another concern in using tires in embankments may be the potentially combustible nature of tires. To reduce the possibility of fire, a protective earth cover may be placed on the top and side slopes of tire embankments. A similar soil cover is recommended for some other lightweight materials, like wood chips, sawdust, slags, ashes, expanded clay or shale, etc. for protection against fire or to prevent leaching of undesirable materials into groundwater. During construction, normal caution is required to avoid any fires in tires stockpiled on the site or embankment tires that have not yet been capped with soil.

Compacted tire chips (about 2x2 in. nominal size) have permeability values equivalent to typical values for coarse gravel (Bressette, 1984). This property of chips renders them suitable for use in subdrainage as an alternate permeable aggregate. As a highly permeable material, pore pressure developments are prevented in tire fills and backfills. Use of tire chips in alternate layers with non-select fills, like clays, silty clays, etc., will provide a shorter drainage path and thus help accelerate consolidation of the layer.

The use of shredded tires in embankments offers the potential benefit of disposing of large volumes of tires in short sections of highway. For example, the use of an asphalt-rubber pavement overlay utilizes only about 3600 tires per miles of 2-lane road while a mile of 2-lane embankment 20-feet high would utilize about 5 million tires (one tire equals approximately one cubic foot loose bulk density before compaction; Read, et al., 1991).

3.12 Summary and Conclusions

A solution to enhance the stability and reduce the settlement of highway structures on slopes and highly compressible soils is to replace the existing material with a material of lower density and/or use lighter weight fills. This section considers the feasibility of using shredded tires as lightweight fill or backfill material in highway structures. The section contains: a brief review of commonly used lightweight materials; physical and chemical characteristics of rubber tires; and a synthesis of field and laboratory studies on incorporating shredded tires in highway embankments. Finally, it presents a brief discussion on the use of shredded tires in highway structures.

Based on a critical analysis of available information on the use of shredded tires in highway structures and a comparison of rubber chips with traditional lightweight materials, it is concluded that the use of shredded tires in highway construction offers technical, environmental, and economic benefits under certain conditions. The salient benefits of using tire chips as a lightweight geomaterial are: reduced weight of fill - helps increase stability, reduce settlements, and correct or prevent slides on slopes; tire chips serve as a good drainage medium, thus preventing development of pore pressures during loading of fills, and can also serve as a substitute for conventional permeable materials for subdrainage; reduces backfill pressures on retaining structures; provides separation to prevent the underlying weak/problem soils from mixing with subgrade/base material; helps conserve energy and natural resources; and can consume large quantities of waste tires, which has a very positive impact on the environment.

Potential problems associated with the use of shredded tires in highway embankments include: leachate of metals and hydrocarbons; fire risk; and large compressibility of tire chips. Drinking water Recommended Allowable Limits (RALs) for Minnesota are found to be exceeded under "worst-case" conditions (MPCA, 1990). However, a recent field study reports that shredded automobile tires show no likelihood of having adverse effects on groundwater quality (Bosscher, et al., 1992). Proper soil cover is required on top and sideslopes of shredded tire embankment for safety against fire. During construction, normal caution is required to be observed against fire in stockpiled tires or in embankment tires that have not yet been capped with soil.

Field studies indicate 10 to 15% settlement of tire embankments under 4 to 6 ft of soil/pavement overburden pressure and average traffic conditions. Potential settlements can be reduced by providing a thicker soil cap and using a rubber-soil mix instead of chips alone.

Detrimental effects of post-construction settlements can be reduced by using tires under flexible pavements only and letting the chips compress under traffic for some time before placing a final surface course. In addition, information on the use of shredded tires in highway structures is severely lacking, some of the areas of major deficiencies are: lack of requisite data on stress-strain and strength behavior of chips, and chip-soil mix for design and prediction of performance of highway structures; long term impact on environments; and potential economic benefits in the use of tire chips in highway structures as lightweight fill.

CHAPTER 4

COMPACTION BEHAVIOR OF RUBBER SOILS

4.1 Introduction

The first phase of this study consisted of determining the compaction behavior of rubber soils. The testing program was formulated to develop quantitative information about the compaction characteristics of the tire chips alone, and also when they are mixed with different soils. The selection of tire chips for this purpose was made considering the capability of laboratory equipment and the type of tire chips which are routinely produced by the various local shredding facilities. The selection of soils for experimental parametric and material behavior studies is always a difficult process, since it requires that soil samples be uniform (e.g., have identical basic index properties such as grain size and Atterberg limits) and also available in large quantities. Natural soils, besides being difficult to procure, rarely meet these requirements.

Careful consideration of various factors, namely: availability of soils, least variability in their properties, and existence of prior data on the soils for comparison led to the conclusion that research objectives set forth for this study could best be accomplished by using manufactured soils and/or prepared natural soils. It was also rationally concluded that two soils, one each from the family of fine grained and coarse grained soils, will be adequate to determine the effects of adding tire chips on the compaction and shear behavior of soils. Keeping these factors in view, Ottawa sand, a manufactured coarse grained soil, and Crosby till, a locally found natural, fine grained soil, were selected for this study. Large quantities of both the soils were procured and prepared to obtain homogeneous samples and also achieve the desired gradation.

The subsequent subsections describe the tire chips, test soils, testing equipment, and experimental procedures. The results from compaction tests on rubber soils are summarized in Tables 4.2 to 4.6 and also presented graphically in Figures 4.2 to 4.4. Finally, the results are critically analyzed to quantify the compaction behavior of rubber-soils. A summary of conclusions is presented at the end of this section.

4.2 Characterization of Tire Chips

4.2.1 Production

Rubber tires are cut into small chips using different types of shredding equipment. Shredding systems are basically of two categories: mobile and stationary. The mobile units are usually small and have a lower output. The horsepower of shredding systems varies from about 30 to more than 375, with capacity of 100 to more than 2000 tires per hour (from whole tires to rough shreds). The steel is pulled from the tire chips as the size of chips is reduced. The amount of steel in tire chips also depends on the state of sharpness of shredder blades. Sharp blades make comparatively cleaner cuts through a shearing process. During shredding operations, the large pieces of steel belt are removed by magnets. The size of chips is governed by the design of a particular machine and the setting of its cutting blades. Small size chips are produced by processing the material many times through the same shredder and/or through more than one shredder. Automatic classifiers are also used which rotate around the shredder cutting chamber and separate finer sizes from coarser ones. The tire chips so produced are of irregular area with the smaller dimension being the size specified by the manufacturer.

4.2.2 Gradation

The tire chips that are being used for this study were supplied by: ASK Shredders Corporation, East Chicago, Indiana; Baker Rubber, South Bend, Indiana; Rubber Materials Handling, East Chicago, Indiana; and Carthage Machine Company, New York. The samples of tire chips vary in size from the No. 4 sieve to 2 inches plus. The rubber chips have generally clean cuts and only a small percent of steel wires are exposed. Free steel wires are not present in the rubber chip. A mechanical analysis was performed on tire chip samples collected from the various shredding agencies, the results of which are plotted in Figure 4.1. The grading curves of various chip samples generally indicate a uniform gradation of tire chip sample.

4.2.3 Specific Gravity

The small size tire chips, especially without steel, are less dense than water and their specific gravity cannot be measured with any of the methods developed for conventional materials. A simple apparatus and a procedure was developed for measuring the specific gravity of tire chips. The apparatus is a simple five gallon plastic bucket with a hole drilled in its side approximately six inches above the base of the bucket which can be closed with a rubber stopper. The bucket is used in conjunction with a sieve having a size smaller than the smallest particle in the sample to be tested, and a sieve cover.

In the beginning of the test, the bucket, sieve, cover, and stopper were first weighed together. Then the sieve and lid were placed in the bucket. With the hole closed, the bucket was filled with water to above the hole. The bucket

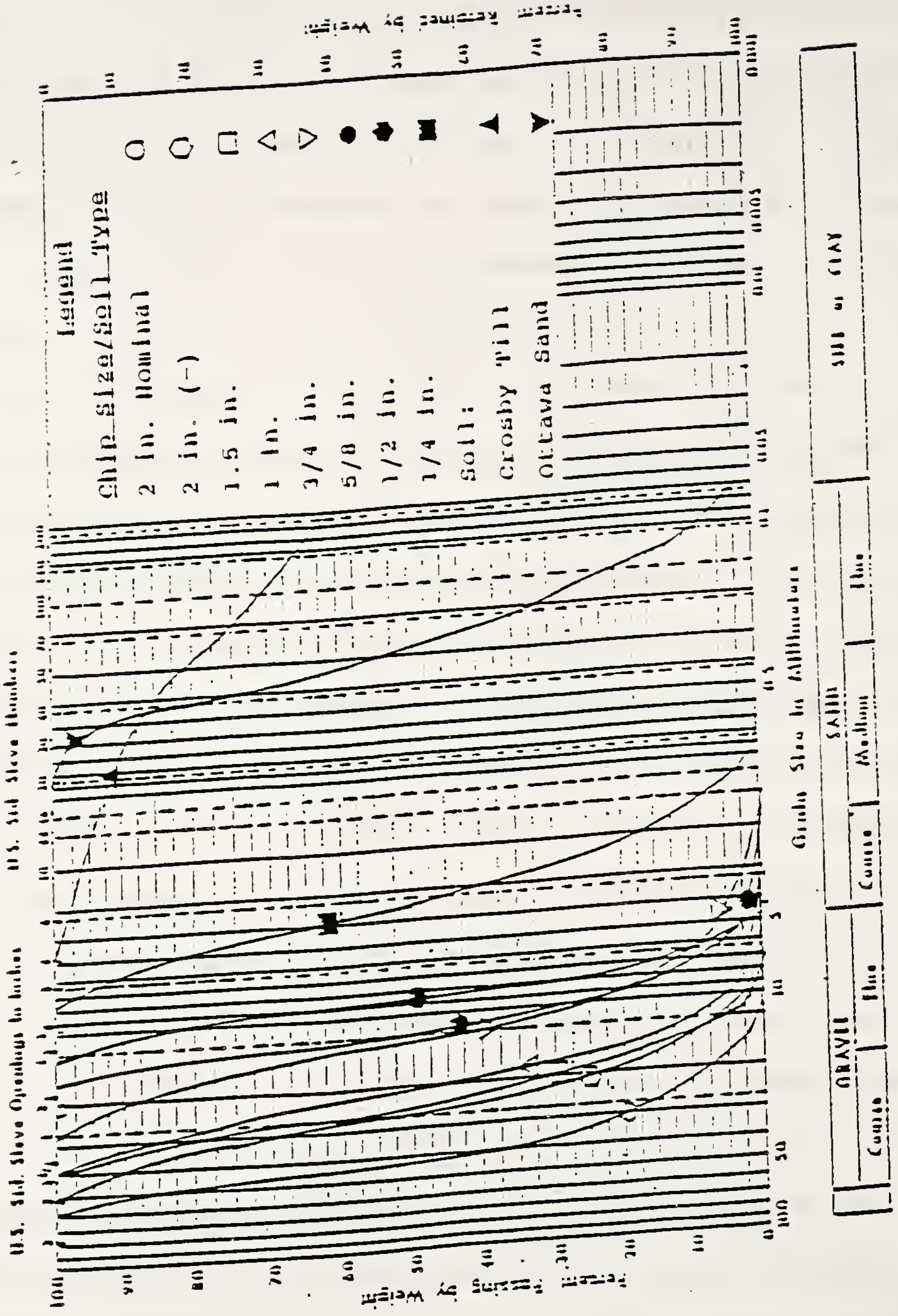


Figure 4.1 Mechanical analysis of test soils and rubber chips

was then placed on a level surface, the stopper was removed, and the water was allowed to flow out until it stopped. The hole was closed with the stopper and the apparatus was weighed. To measure the specific gravity of a tire chip sample, a similar procedure was followed except the sieve and cover assembly were filled with a sample of tire chips of known weight before it was immersed into the water. The sieve weighed enough to drag the tire chips down into the water.

The specific gravity of the chips was determined using the following relationship:

$$G_c = \frac{W_c}{(W_1 + W_c - W_2)} \qquad (4.1)$$

Where

G_c = Specific gravity of tire chips

W_c = Weight of tire chips sample, dry

W_1 = Weight of assembly, including bucket, sieve, lid, stopper, and water

W_2 = Weight of assembly with chips sample, i.e., bucket, sieve, lid, stopper, water, and chips

Two sources of error are identified `in this method, which may effect the measured values of specific gravity: 1) the possibility of trapped air bubbles in the chips; and 2) the increase of water content of the chips due to some absorption of water while the bucket drains and the measurements are taken. The possibility of presence of some air bubbles in the specimen cannot be simply eliminated. However, it can be minimized by using de-aired water. The error due to absorption of water by chips can be reduced by measuring the specific gravity of a saturated tire chip sample. The chip samples are prepared for testing by immersing them in water for at least one week and then the water content is determined in a surface dried state before testing (see subsequent subsection). The water content of chips are not likely to change significantly during a relatively short testing period.

The bulk specific gravity in a surface dried saturated state was measured for tire chips of sizes varying from 0.50 to 2-inch. The measured values of specific gravity for tire chips ranged from 0.88 to 1.13. The average values of specific gravity for chips having sizes of 0.50, 0.75, 1.00, 1.50, and 2-inch were computed as 0.88, 0.95, 1.02, and 1.13, respectively. The values depended upon the type of chips, size of chips, and the amount of steel present in the chips. It is found that some bias exists in selecting the sample and it is difficult to quantify or accurately characterize each sample. Qualitatively, the chips from fiber glass tires yielded lower values of specific gravity than the chips from steel belted tires. Similarly, smaller size chips of steel belted type of tires had lower specific gravity than larger size chips, mainly due to the fact that steel is pulled out as the size of chips is reduced. The chips with exposed steel wires yielded higher values of specific gravity relative to the chips having cleaner cuts.

Humphrey et al. (1992) reports the values of specific gravity determined using ASTM C127 for three types of tire chips specimens: samples of chips made from a mix of steel and glass belted tires, samples manually separated into chips containing only glass belts, and samples manually separated into chips containing only steel belts. The specific gravity in a saturated surface-dry condition has been reported as 1.05 for the mix of steel and glass belts, 1.02 for glass belts only, and 1.10 for steel belts only.

4.2.4 Water Absorption

The absorption was determined for the various types of tire chips used for this research. The air-dried chips were weighed and then soaked in water for 24 hours. After soaking, chips were surface dried and weighed. The absorption was taken as the difference between the two weights divided by the dry weight, expressed as a percentage. The absorption for different types of chips ranged from 1% to

2.5%. Generally, the smaller size chips, with exposed fiber threads, had higher absorption than the larger size chips, with no exposed fibers.

Humphrey et al. (1992) determined the values of tire chips absorption using AASHTO designation T 85-85 (see AASHTO, 1986). The essential difference between this procedure and that followed by the author is that AASHTO defines absorption as the difference between the surface dried saturated and oven dried weights of the specimen. Humphrey et al. (1992) reported that the values of absorption for three types of chips ranged from 2.0% to 4.3%.

4.3 Test Soils

4.3.1 Crosby Till

One of the soils used for this research study is Crosby till, which is a natural fine grained soil. The soil was obtained from about 200 m west of the intersection of McCormick and Cherry Lane, West Lafayette, Indiana. The development in Lafayette and its environs provided opportunities for extensive research on this soil at Purdue University, which stimulated interest in understanding its basic behavior. The soil can be conveniently obtained and has been routinely used in many research studies over the years at Purdue University (e.g., Holtz and Kovacs, 1981). The test soil was prepared in the laboratory to eliminate the possibility of spatial variability in the properties of this natural soil and correctly understand the effects of adding tire chips on the shear and compaction behavior of soil.

Preparation of the test soil included: air drying a large quantity of soil, which was considered sufficient to meet the testing requirements of this study; sieving the natural soil through a US Standard No. 4 sieve to remove gravel particles or organic materials; thoroughly mixing the soil to achieve homogeneity; and storing the soil in sealed containers. Index tests have been performed on the soil samples from various containers and the soil has been found to be fairly homogeneous. The soil has been classified as CL-ML (sandy silty clay) according to the Unified Soil Classification System (USCS) and A-4(0) as per the American Association of State Highway and Transportation Officials (AASHTO) classification system. The data obtained through the mechanical analysis of this soil is plotted in Figure 4.1. Some of the engineering properties of this soil are summarized in Table 4.1.

4.3.2 Ottawa Sand

The sand used in this study was manufactured by U.S. Silica, Ottawa, Illinois and is sold under the trade name Ottawa sand. It is white medium to fine sand. The desired gradation was achieved by mixing three different types of

Table 4.1 Summary of properties of soils used in this study

Physical Properties	Crosby Till	Ottawa Sand
Liquid Limit (%)	19.8	-
Plastic Limit (%)	15.5	NP
Plasticity Index (%)	4.3	NP
Maximum Dry Density:	-	-
Modified Proctor (pcf)	130.25	-
Standard Proctor (pcf)	124.1	-
Vibration Method (pcf)	-	118.75
Optimum Water Content:	-	-
Modified Proctor (%)	9.3	-
Standard Proctor (%)	10.6	-
Soil Classification:		
Unified Soil Classification	CL-ML (Sandy Silty Clay)	SP (Poorly Graded Sand)
AASHTO Soil Classification	A-4(0)	A-3(0)

Ottawa sands in equal proportions, namely: Flintshot (AFS Range 26-30); #17 Silica (AFS Range 46-50); and F-125 (AFS Range 115-130). The grain size distribution curve of the test soil is plotted in Figure 4.1. The sand is classified as SP (poorly graded sand) according to the USCS and A-3(0) as per the AASHTO classification system. Salient engineering properties of the soil are summarized in Table 4.1.

4.4 Description of Testing Equipment

The compaction tests conducted for this research were performed using a mechanical compactor, manual impact Proctor type hammer, and an electromagnetic, vertically vibrating table. The mechanical compactor used for this study was developed and manufactured by Soiltest, Inc. The apparatus is equipped with a device to control the height of drop to a free fall of 12 in. or 18 in. (depending upon the setting) above the elevation of the soil, and uniformly distribute such drops to the soil surface. The mechanical compactor is designed with a height adjustment for each blow, all subsequent blows have a rammer free fall of 12 in. or 18 in. measured from the elevation of the soil as compacted by the previous blow. When used with the 4-in. mold, the specimen contact face is circular with a diameter of 2.00 in. When used with the 6-in. diameter mold, the specimen contact face has the shape of a section of a circle of a radius equal to 2.90 in. The sector face rammer operates in such a manner that the vertex of the sector is positioned at the center of the specimen. The rammer weighs 5.5 lb. The rammer shaft is hollow inside and can accommodate an additional shaft to increase the rammer weight to 10 lb, if required.

4.5 Experimental Procedures

The compaction tests on Crosby till were performed following procedures described in ASTM D 698 (AASHTO: T99-61) and D 1557 (AASHTO: T180-61). A mechanical rammer and 6-in. diameter mold were used to perform the compaction tests. Three different compactive efforts were used: 1) sample compacted in 5 equal layers with 56 blows/layer of 10-lb hammer with an 18-in drop (i.e., modified Proctor method); 2) sample compacted in 3 equal layers with 56 blows/layer of 5.5-lb hammer with a 12-in. drop (i.e., standard Proctor method); and 3) sample compacted using a procedure similar to standard Proctor with number of blows per layer adjusted to give the compactive effort equivalent to 50% of standard Proctor.

The compaction tests on Ottawa sand were performed using procedures described in ASTM D4253. An electromagnet, vertically vibrating table was used for providing the desired level of vibration. Oven dried sand and rubber-sand mix were placed in a 4-in. diameter compaction mold under 2 psi surcharge applied to the surface of the specimen. The dry density was computed after vibrating the specimen for 8 minutes at 60 Hz.

4.6 Laboratory Testing Program

The laboratory testing program was formulated to accomplish the research objectives set forth in Chapter One. During the compaction phase of this study, the samples were compacted using two different methods, i.e., Proctor method of compaction for Crosby till and vibration method for Ottawa sand. In the case of Crosby till, the optimum moisture contents were determined for modified and standard compactive efforts. The optimum moisture content were also determined for rubber-soil mix with 15.8% and 30.5% percent of 1-inch chips compacted using standard compactive effort in a 6-inch Proctor mold. The samples of Crosby till were prepared at the optimum moisture content (which was the same for soil alone and rubber-soil mix), then placed in a container, sealed and stored in a humid room for 24 hours prior to testing. The compaction tests were then performed on rubber-soil samples. The variables considered included: compactive effort, size of chips, and the ratio of soil/chips. Three different compactive efforts were used, i.e., modified Proctor, standard Proctor, and 50% of standard Proctor. The tire chips of seven different sizes ranging from sieve No. 4 to 2 inches plus are being investigated in this study. The soil/chip ratios were varied from pure soil to pure chips (i.e., quantity of chips in mix varied from 0 to 100% of dry weight of soil).

In the case of Ottawa sand, the soil was oven dried and then compacted using a vibratory table (see ASTM 4253). First, the maximum density of the sand was determined through a number of trials, and then the sand was mixed with rubber chips in different ratios. In the chip/sand mix, the quantity of tire chips was varied from 0 to 100% of dry weight of soil (i.e., from pure sand to pure chips).

In the subsequent phases of this research study, the stress-strain and strength behavior of compacted rubber soils were determined under static and dynamic loading conditions. In addition, constant head permeability tests were also conducted on the laboratory prepared rubber-soils specimens. The tests samples in all the cases were prepared in the laboratory following procedures described above. The results from the compaction phase of each type of laboratory tests are also included in the subsequent subsection for comparison and also for understanding the compaction behavior of rubber-soils.

4.7 Presentation of Test Results

Table 4.1 presents the engineering properties of test soils. Figure 4.1 is a plot of the results of mechanical analysis performed on the tire chips and the test soils. The results from compaction testing of rubber soils have been summarized in Tables 4.2 to 4.5. Tables 4.2 to 4.4 tabulate the individual test results from chips alone, chips-sand, and chips-Crosby, respectively. Table 4.5 summarizes the results for compaction tests on chips alone and also for rubber-soils, giving mean, one standard deviation, and coefficient of variation, to facilitate the understanding of compaction behavior. The results have also been presented graphically in Figures 4.2 to 4.4. Figure 4.2 compares the compaction curves on dry density versus percent chips for all the tests performed on rubber soils. Figure 4.3 gives a typical compaction curve for rubber-soils. Figure 4.4 presents the compaction results on tire chips alone using different compaction methods and also varying the compactive efforts.

4.8 Discussion

Table 4.2 summarizes the results from compaction testing of tire chips of different sizes. The samples were prepared using different compaction methods, i.e., vibration and impact, Proctor type compaction. The compactive energy was also varied from modified Proctor energy to no compaction. The data show remarkably consistent results, with the exception of some tests conducted using small compaction molds, i.e., 4 or 6-inch molds. The smaller mold yields

Table 4.2 Results from compaction tests on tire chips

Test No.	Chips Size (inch)	Method of Sample Preparation	Dry Density (pcf)	Remarks
CTC07	2.00	Modified	41.71	
CTC05	2.00	Standard	39.62	
CTC01	2.00	50% Standard	38.33	
CTC09	2.00	No Compaction	29.08	
CTC02	1.50	50% Standard	40.25	
CTC08	1.00	Modified	42.50	
TPC01	1.00	Modified	42.33	
TPC02	1.00	Modified	42.85	
TPC03	1.00	Modified	43.73	
PERM04	1.00	Modified	42.38	
COMPM04	1.00	Modified	34.68	too low
CTC06	1.00	Standard	40.95	
TPC04	1.00	Standard	40.39	
TPC05	1.00	Standard	41.13	
TPC06	1.00	Standard	40.68	
TPC07	1.00	Standard	41.57	
TPC08	1.00	Standard	40.45	
PERM01	1.00	Standard	40.58	
PERM02	1.00	Standard	40.35	
COMPS04	1.00	Standard	36.64	too low
CTC03	1.00	50% Standard	39.57	
TPC09	1.00	50% Standard	40.10	
TPC10	1.00	50% Standard	40.35	
TPC11	1.00	50% Standard	40.26	
PERM03	1.00	50% Standard	39.67	
COMPHS04	1.00	50% Standard	35.41	too low

Table 4.2, Continued

Test No.	Chips Size (inch)	Method of Sample Preparation	Dry Density (pcf)	Remarks
CTS10	1.00	Vibration	32.75	
COMPV04	1.00	Vibration	29.15	
CTC10	1.00	No Compaction	30.50	
COMPM03	0.75	Modified	34.68	too low
COMPS03	0.75	Standard	35.56	too low
COMPV03	0.63	Vibration	30.64	
COMPM02	0.50	Modified	34.62	too low
TPC12	0.50	Standard	39.99	
TPC13	0.50	Standard	39.05	
TPC14	0.50	Standard	39.00	
MR06	0.50	Standard	39.87	
COMPS02	0.50	Standard	35.29	too low
COMPV03	0.50	Vibration	29.51	
COMPM01	0.25	Modified	33.94	too low
COMPS01	0.25	Standard	37.17	
COMPV01	0.25	Vibration	34.01	

Notes:

1. Modified = modified Proctor energy = 56,250 ft-lb/ft^3.
2. Standard = standard Proctor energy = 12,375 ft-lb/ft^3.
3. 50% Standard = half the standard Proctor energy = 6188 ft- lb/ft^3.
4. Lower values of dry density are generally obtained from the compaction tests conducted using smaller size molds.

Table 4.3 Compaction results from tests on rubber-sand

Test No.	Chip Size (inch)	Tire Chips (%)	Dry* Density (pcf)	Remarks
COMPRS01-4	-	0.00	118.75	* mean of 4 tests.
CTS01	-	0.00	116.25	
TRS01	-	0.00	115.68	
TRS02	-	0.00	115.77	
TRS03	-	0.00	115.30	
MR01	-	0.00	115.32	
PERM05	-	0.00	118.13	
COMPRS05	1.00	4.76	115.02	
COMPRS06	0.63	4.76	114.94	
COMPRS07	0.50	4.76	113.82	
COMPRS08	0.25	4.76	113.40	
COMPRS09	1.00	9.09	110.04	
COMPRS10	0.63	9.09	110.79	
COMPRS11	0.50	9.09	108.95	
COMPRS12	0.25	9.09	108.45	
COMPRS13	1.00	13.04	106.65	
COMPRS14	0.63	13.04	106.70	
COMPRS15	0.50	13.04	105.42	
COMPRS16	0.25	13.04	102.92	
MR02	0.50	15.00	100.75	
PERM06	1.00	15.48	104.79	
TRS04	1.00	16.5	101.55	
TRS05	1.00	16.50	103.02	
TRS06	1.00	16.50	103.18	
COMPRS17	1.00	16.67	101.76	

Table 4.3, Continued

Test No.	Chip Size (inch)	Tire Chips (%)	Dry• Density (pcf)	Remarks
COMPRS18	0.63	16.67	102.01	
COMPRS19	0.50	16.67	101.98	
COMPRS20	0.25	16.67	100.91	
CTC03	1.00	16.70	103.82	
COMPRS21	1.00	20.00	99.27	
COMPRS22	0.63	20.00	98.42	
COMPRS23	0.50	20.00	97.81	
COMPRS24	0.25	20.00	95.70	
COMPRS25	1.00	23.08	96.95	
COMPRS26	0.63	23.08	95.20	
COMPRS27	0.50	23.08	94.83	
COMPRS28	0.25	23.08	92.37	
CTS04	1.00	23.10	99.34	
COMPRS29	1.00	25.93	93.15	
COMPRS30	0.63	25.93	93.03	
COMPRS31	0.50	25.93	92.79	
COMPRS32	0.25	25.93	91.83	
TRS07	1.00	29.16	96.17	
TRS08	1.00	29.16	94.20	
TRS09	1.00	29.16	94.22	
MR03	1.00	30.00	90.28	• low
PERM07	1.00	30.07	95.53	
CTS05	1.00	31.30	91.66	
CTC06	1.00	37.00	86.09	
PERM08	1.00	37.72	88.08	
TRS19	0.50	37.85	87.11	

Table 4.3, Continued

Test No.	Chip Size (inch)	Tire Chips (%)	Dry* Density (pcf)	Remarks
TRS20	0.50	37.85	86.32	
TRS21	0.50	37.85	87.11	
MR07	0.75	38.00	85.08	
MR04	0.50	38.00	86.45	
TRS22	1.00	38.78	88.28	
TRS23	1.00	39.32	89.25	
TRS24	1.00	39.37	88.94	
TRS20	0.50	39.79	78.84	* too low
TRS10	1.00	40.00	84.61	
TRS11	1,00	40.00	84.61	
TRS12	1.00	40.00	85.02	
CTC07	1.00	44.00	73.13	
MR05	0.50	50.00	74.03	
TRS13	1.00	50.00	72.28	
TRS14	1.00	50.00	73.08	
TRS15	1.00	50.00	72.73	
CTS08	1.00	50.00	64.40	* low
TRS16	1.00	66.54	55.08	
TRS17	1.00	66.54	54.41	
TRS18	1.00	66.54	54.68	
CTC09	1.00	49.66	66.70	

Table 4.4 Compaction results from tests on chips-Crosby till

Test No.	Size of Chips (inch)	Chip/Mix Ratio (%)	Compactive Effort	Dry Density (pcf)
COMPM1-4	No chips	0.00	Modified	130.25
COMRCM05	1.00	4.76	Modified	121.83
COMRCM06	0.75	4.76	Modified	122.3
COMRCM07	0.50	4.76	Modified	120.74
COMRCM08	0.25	4.76	Modified	117.38
COMRCM09	1.00	9.09	Modified	116.51
COMRCM10	0.75	9.09	Modified	116.43
COMRCM11	0.50	9.09	Modified	114.95
COMRCM12	0.25	9.09	Modified	110.85
COMRCM13	1.00	16.67	Modified	104.64
COMRCM14	0.75	16.67	Modified	101.97
COMRCM15	0.50	16.67	Modified	102.17
COMRCM16	0.25	16.67	Modified	96.99
COMRCM17	1.00	28.57	Modified	89.7
COMRCM18	0.75	28.57	Modified	85.6
COMRCM19	0.50	28.57	Modified	82.31
COMRCM20	0.25	28.57	Modified	79.39
COMRCM21	0.50	33.33	Modified	79.78
COMRCM22	0.25	33.33	Modified	73.99
COMP1-4	No Chips	0.00	Standard	124.10
CRC01	No Chips	0.00	Standard	119.13
TRC01	No Chips	0.00	Standard	119.21
TRC02	No Chips	0.00	Standard	119.67
TRC03	No Chips	0.00	Standard	119.02
COMRCS01	1.00	4.76	Standard	118.56
COMRCS02	0.75	4.76	Standard	116.42
COMRCS03	0.50	4.76	Standard	116.85

Table 4.4, Continued

Test No.	Size of Chips (inch)	Chip/Mix Ratio (%)	Compactive Effort	Dry Density (pcf)
COMRCS04	0.25	4.76	Standard	120.76
COMRCS05	1.00	9.09	Standard	111.63
COMRCS06	0.75	9.09	Standard	110.32
COMRCS07	0.50	9.09	Standard	111.87
COMRCS08	0.25	9.09	Standard	107.65
PERM10	1.00	14.83	Standard	106.37
CRC02	2.00	15.43	Standard	99.11
TRC04	1.00	16.27	Standard	100.94
TRC05	1.00	16.27	Standard	101.5
TRC06	1.00	16.27	Standard	101.00
COMRCS09	1.00	16.67	Standard	100.88
COMRCS10	0.75	16.67	Standard	101.50
COMRCS11	0.50	16.67	Standard	99.99
COMRCS12	0.25	16.67	Standard	94.51
COMRCS13	1.00	28.57	Standard	84.61
COMRCS14	0.75	28.57	Standard	86.29
COMRCS15	0.50	28.57	Standard	85.62
COMRCS16	0.25	28.57	Standard	79.05
PERM11	1.00	30.08	Standard	86.67
TRC07	1.00	30.18	Standard	89.17
TRC08	1.00	30.18	Standard	88.17
TRC09	1.00	30.18	Standard	88.23
CRC03	2.00	30.42	Standard	78.30
COMRCS17	1.00	33.33	Standard	79.20
COMRCS18	0.75	33.33	Standard	77.50

Table 4.4, Continued

Test No.	Size of Chips (inch)	Chip/Mix Ratio (%)	Compactive Effort	Dry Density (pcf)
COMRCS19	0.50	33.33	Standard	73.80
COMRCS20	0.25	33.33	Standard	74.91
CRC04	2.00	39.97	Standard	71.28
CRC07	1.00	40.00	Standard	72.53
PERM12	1.00	40.00	Standard	74.84
TRC10	1.00	40.05	Standard	81.41
TRC11	1.00	40.05	Standard	81.01
TRC12	1.00	40.05	Standard	81.13
TRC13	1.00	48.49	Standard	71.56
TRC14	1.00	48.49	Standard	70.88
TRC15	1.00	48.49	Standard	71.74
CRC05	2.00	49.98	Standard	62.67

Notes:

1. Modified = modified Proctor energy = 56,250 ft-lb/ft^3.
2. Standard = standard Proctor energy = 12,375 ft-lb/ft^3.

Table 4.5 Summary of results from compaction testing of rubber-soils

Chip Size (inch)	No. of Tests	Soil Type (% Chips)	Method of Sample Preparation	Dry Density (pcf)±1SD (COV)
2.00	1	No Soil	Modified	41.71
2.00	1	No Soil	Standard	39.62
2.00	1	No Soil	50% Standard	38.33
1.50	1	No Soil	Standard	40.25
2.00	1	No Soil	No Compaction	29.08
1.00	5	No Soil	Modified	42.76±0.519 (1.21%)
1.00	8	No Soil	Standard	40.76±0.398 (0.98%)
1.00	5	No Soil	50% Standard	39.99±0.314 (0.79%)
1.00	2	No Soil	Vibration	30.95
1.00	1	No Soil	No Compaction	30.50
0.50	4	No Soil	Standard	39.48±0.455 (1.15%)
0.50	1	No Soil	Vibration	29.51
No Chips	4	Sand (0.00)	Vibration	118.75
0.25-1	4	Sand (4.76)	Vibration	114.30±0.701 (0.614%)
0.25-1	4	Sand (9.09)	Vibration	109.56±0.915 (0.835%)
0.25-1	4	Sand (13.04)	Vibration	105.42±1.533 (1.454%)
0.25-1	8	Sand (16.61)	Vibration	102.28±0.822 (0.803%)
0.25-1	4	Sand (20.00)	Vibration	97.80±1.319 (1.348)
0.25-1	4	Sand (23..08)	Vibration	94.84±1.634 (1.723%)
0.25-1	4	Sand (25.93)	Vibration	92.70±0.269 (0.290%)

Table 4.5, Continued

Size of Chips	No. of Tests	Soil Type (% Chips)	Method of Sample Preparation	Dry Density (pcf)±1SD (COV)
0.50-1	14	Sand (38.68± 0.74)	Vibration	86.13±2.510 (2.91)
0.50-1	4	Sand (50.00)	Vibration	73.03±0.643 (0.881%)
1.00	4	Sand (66.54)	Vibration	54.72±0.335 (0.612%)
No Chips	4	Crosby (0.00)	Modified	130.25
0.50-1	3	Crosby (4.76)	Modified	121.62±1.110 (0.915%)
0.50-1	3	Crosby (9.09)	Modified	115.97±1.343 (1.158%)
0.50-1	3	Crosby (16.67)	Modified	102.93±1.214 (1.180%)
0.50-1	3	Crosby (28.57)	Modified	85.870±3.022 (3.520%)
No Chips	4	Crosby (0.00)	Standard	124.10
0.50-1	3	Crosby (4.76)	Standard	117.28±0.924 (0.788%)
0.50-1	3	Crosby (9.09)	Standard	111.27±0.681 (0.612%)
0.5-1	6	Crosby (16.47)	Standard	100.97±0.505 (0.500%)
0.50-1	3	Crosby (28.57)	Standard	85.51±0.691 (0.808%)
0.50-1	4	Crosby (30.18)	Standard	88.06±0.895 (1.016%)
0.50-1	3	Crosby (33.33)	Standard	76.35±2.211 (2.895%)

Table 4.5, Continued

Size of Chips (inch)	No. of Tests	Soil Type (Percent Chips)	Method of Sample Preparation	Dry Density (pcf) ±1SD (COV)
1.00-2	6	Crosby (40.02)	Standard	77.03±4.280 (5.556%)
1.00-2	4	Crosby (48.49)	Standard	71.39±0.370 (0.519%)

Notes:
1. Most of the values of dry density are average ± one standard deviation.
2. Individual test data summarized in this table can be found in Tables 4.2, 4.3 and 4.4.
3. COV = Coefficient of Variation (dry density) = (SD/Mean).

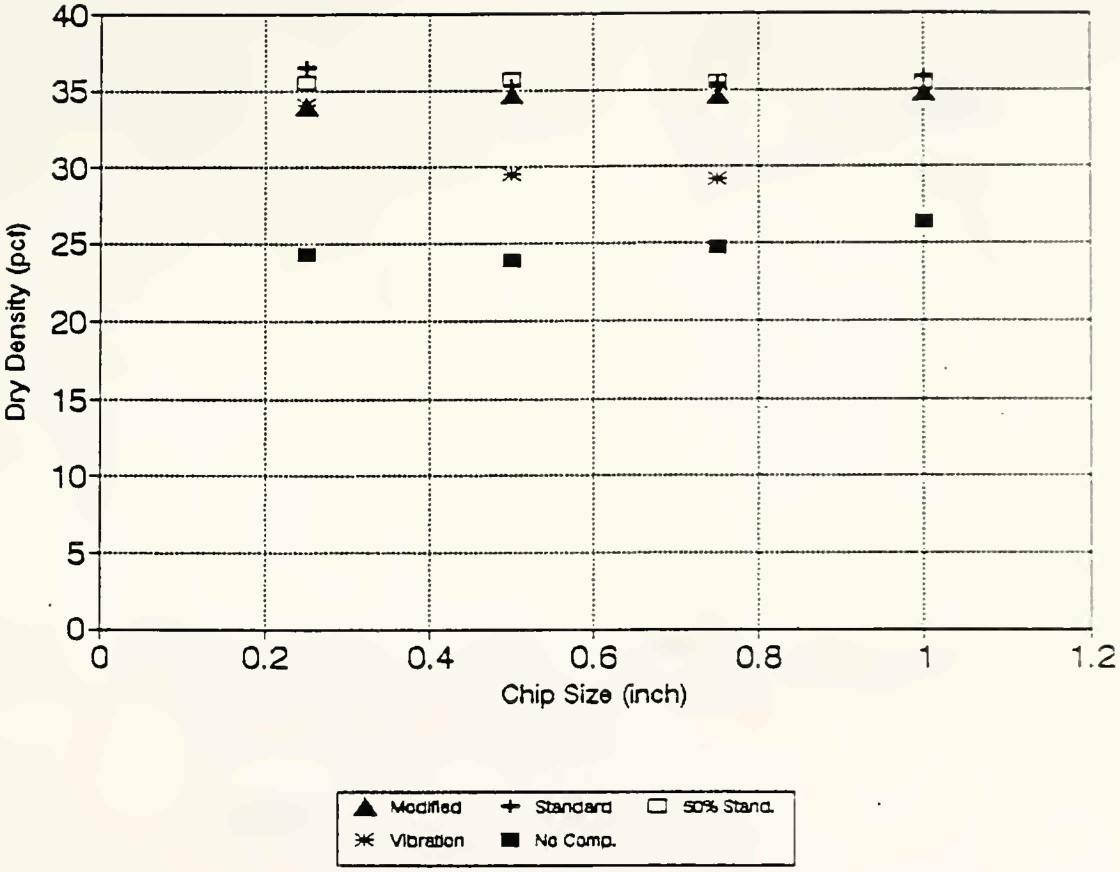


Figure 4.2 Dry density versus chip size for different methods of compaction and compactive energy levels

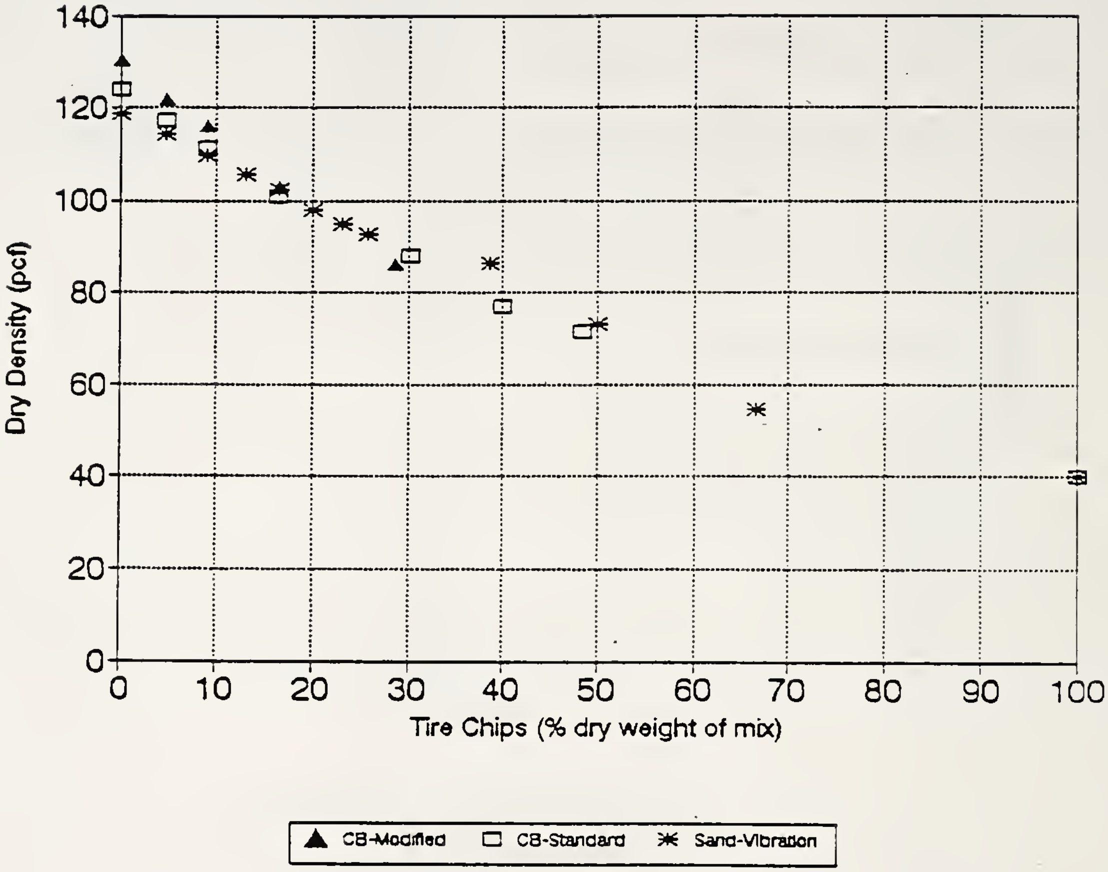


Figure 4.3 Comparison of compaction curves from tests on rubber-soils

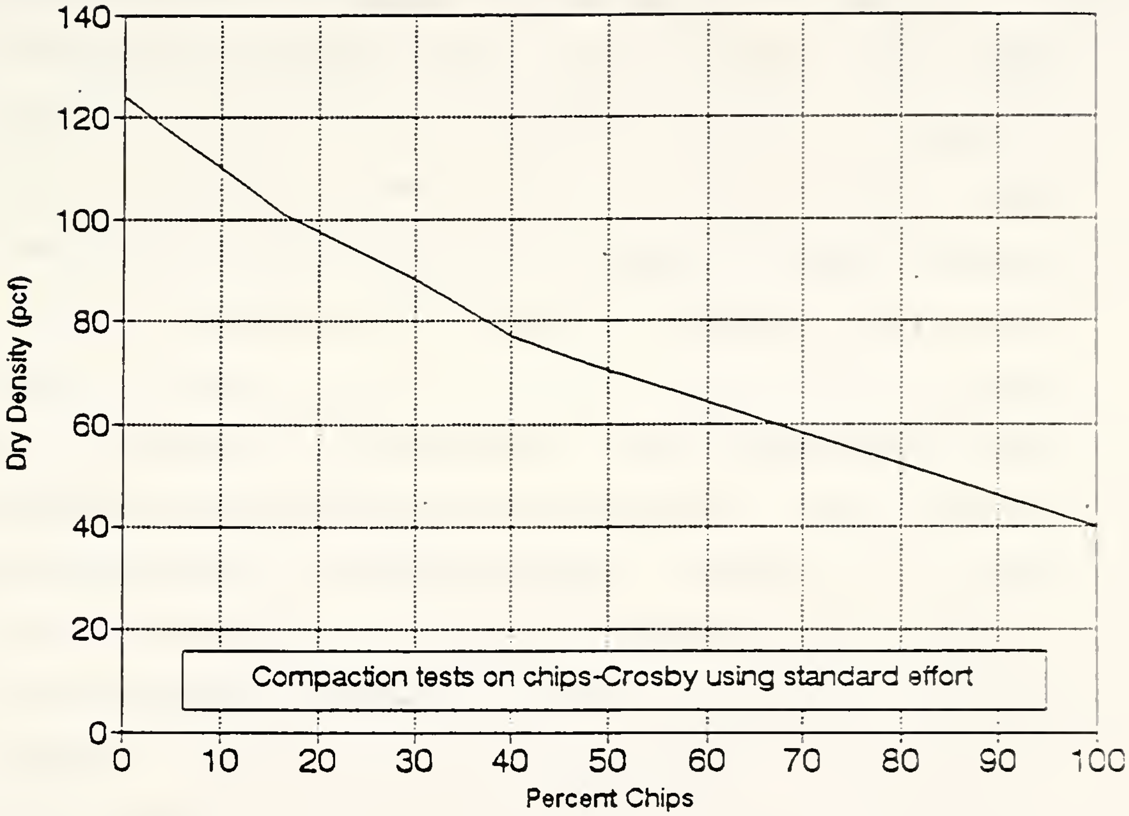


Figure 4.4 A typical compaction curve from tests on rubber-Crosby till compacted using standard Proctor energy

density of chips which is about 10 to 15% lower than the larger molds (i.e., 8/12-inch), for the same chip sizes and compactive energy.

Figure 4.2 compares the compaction results from tests performed on rubber chips using different methods and also varying the compactive efforts on a density versus size of rubber chips plot. It is known that higher compactive effort yields higher dry density, but this trend was not observed from the experimental results on pure chips. In fact, the opposite of this was found in case of Proctor compaction tests on rubber chips. The density of chips was slightly reduced with an increase in compactive effort from standard to modified Proctor compaction method. However, the results obtained were almost similar to the standard Proctor compaction method when the compactive effort was reduced to 50 percent. The density of rubber chips obtained from vibratory compaction was lower than those obtained using the Proctor compaction method. However, the density computed without any compaction was the lowest. This indicates that some compaction is necessary, even though the optimum density can be achieved with a modest compactive effort.

The size of chips is found to have a negligible effect on the density of chips, except in case of vibration compaction. This is presumably due to the fact that smaller size chips have a lower specific gravity (see Subsection 4.2.3), but are easy to compact into a dense state, while larger size chips have a higher specific gravity due to a larger amount of steel in them, but are difficult to compact into a dense state. The density achieved using vibration compaction decreases with increasing chip size, which is expected since smaller size rubber particles rearrange easily under vibration and achieve better packing. However, vibratory compaction is found to be comparatively not very effective in the case of chip sizes larger than 0.25-inch.

Table 4.3 summarizes the data from compaction tests on rubber-sand using the vibration method. It is found that the density decreases with increase in percent chips and that the size of chips does not have significant effect on the density of the rubber-sand mix. However, a trend of increasing density was found with increase in the size of chips, with the exception of compaction tests on 5/8 in. size chips which yielded density greater than 1-in. chips in certain cases. This is presumably due to a more uniform gradation of 5/8 in. size chips (see Figure 4.1), and thus larger voids which when filled with sand increase the density of the chip-sand mix.

Table 4.4 summarizes the results from compaction tests on rubber-Crosby till conducted using Proctor type compaction with impact energy equal to modified and standard Proctor compaction tests. Similar to the results from compaction tests on rubber-sand, the size of chips does not have a significant effect on the resulting density. However, a trend of increasing density with increasing size of chips is observed.

Table 4.5 presents a summary of results from tests on rubber-soils giving mean, one standard deviation, and the coefficient of variation for mixes containing almost the same percent of chips. The data are then plotted in Figure 4.3. The data indicate: 1) the variation in density of rubber-soils is almost linear with increase in percent chips; 2) the density for rubber-Crosby specimens prepared using modified compactive effort is higher than the density of a mix containing the same percent of chips, but compacted with the standard Proctor energy, for up to 20% chips by weight of mix; 3) the density of rubber-sand is slightly lower than the density of rubber-Crosby up to 20% of chips by the weight of mix; and 4) the data from tests with chips more than 20% by the weight of mix for all the specimens almost overlap.

Figure 4.4 is a typical compaction curve plot from tests on rubber-Crosby compacted with energy equivalent to standard Proctor test. The curve demonstrates the compaction behavior of rubber-soils. The curve has three segments, each with distinctly different slopes: 1) the first segment is from 0%

to about 20% chips, the portion where density is influenced by the type of soil, method of compaction, and compactive effort - the portion of the curve where the behavior of soils governs the density of rubber-soils; 2) 20% to about 40% chips - the influence of soils gradually diminishes and the behavior of chips starts prevailing; and 3) beyond 40% chips - the portion of curve where chips control the behavior of rubber-soils mixes.

A linear regression analysis was performed on the data from rubber-soils for density (pcf) versus percent chips and the results are summarized in Table 4.6. The following three correlation are developed for prediction of density for the rubber-soils:

$$(\gamma_d)_{rs}=115.8-0.816P \tag{4.2}$$

$$(\gamma_d)_{rcbm}=129.6-1.549P \tag{4.3}$$

$$(\gamma_d)_{rcbs}=117.4-0.84P \tag{4.4}$$

Where

$(\gamma_d)_{rs}$ = dry density of chip-sand in pcf

Table 4.6 Linear regression results for dry density (pcf) versus percent chips relationship for rubber-soils

Type of Mix	Method of Sample Preparation	Intercept	Slope	r^2
Chip-Sand	Vibration	115.81	-0.816	0.982
Chip-CB	Modified	129.63	-1.549	0.998
Chip-CB	Standard	117.41	-0.840	0.963

Notes:

1. Modified = modified Proctor energy = 56,250 ft-lb/ft^3.
2. Standard = standard Proctor energy = 12,375 ft-lb/ft^3
3. The relationship in the case of compaction of Crosby by modified Proctor energy is valid up to 20% chip/mix ratios.
4. CB = Crosby till.

$(\gamma_d)_{rcbm}$ = dry density of chip-Crosby till in the case of compaction with modified Proctor energy in pcf

$(\gamma_d)_{rcbs}$ = dry density of chip-Crosby till in the case of compaction with standard Proctor energy in pcf

P = percent chips of the weight of rubber-soil mix

Equations 4.2, 4,3, and 4.4 can be used for prediction of density for rubber-sand, rubber-Crosby using modified compactive effort, and rubber-Crosby using standard compactive effort, respectively. It is found that Equation 4.3 is valid only up to 20% chips by weight of mix. Equation 4.4 can be used even for rubber-soil mixes prepared using modified compactive effort for chip ratios greater than 20%.

4.9 Summary and Conclusions

Two types of soils, representing fine and coarse grained, have been used for this research: (1) Ottawa sand - classified as poorly graded sand (SP) according to USCS and A-3(0) as per the AASHTO classification system; and (2) Crosby till - classified as sandy silty clay (CL-ML) as per USCS and A-4(0) according to AASHTO. Shredded tire chips used in this research were procured from various tire processing agencies and their size varied from sieve No. 4 to 2 in. The first phase of this study consisted of determining the compaction behavior of rubber soils.

During this phase of the research, the testing program was formulated to develop quantitative information about the compaction characteristics of rubber soils and chips alone. The variables considered included: compaction methods, compactive efforts, tire chip sizes, chip/soil ratios, and size of compaction mold. The compaction tests were conducted following methods described in ASTM specifications D 698 (AASHTO: T99-61), D 1557 (AASHTO: T180-61) and D4253. Three different compactive efforts were used, i.e., modified Proctor, standard Proctor, and 50% of standard Proctor. The tire chips of seven different sizes ranging from sieve No. 4 to 2 inches have been investigated. The soil/chip ratios were varied from pure soil to pure chips (i.e., quantity of rubber chips was varied from 0 to 100% of dry weight of mix).

The following conclusions are drawn, based on a critical analyses of the results obtained from the compaction testing of rubber-soils and rubber chips alone.

- Vibratory methods of compaction are suitable for rubber-sands. Non-vibratory methods (e.g., Proctor type compaction) are more appropriate for compacting mixes of chips and fine grained soils.
- Although, a mold six times the maximum size of chips is considered adequate for conducting compaction tests on rubber-soils, it has been found that size of the mold effects the maximum density

of rubber-soils. The small size molds (4 to 6 in.) may yield densities which may be about 10 to 15% lower than those obtained with larger molds (8 to 12 in.) for the same size of chips.

- The effect of compactive effort on the resulting density of rubber-soils decreases with increasing chip/soil ratios. Only a small effect is observed for an amount of chips greater than 20% of the dry weight of mix. Similarly, the density of chips alone is also not much affected by the compactive effort. Only a modest compactive effort is required to achieve the maximum density of chips. This density is about one third that of conventional soil fills.
- Density of rubber-soils decreases with increasing chip/soil ratios and the relationship between density versus percent chips is almost linear. Correlations are developed (see Equations 4.2, 4.3, and 4.4) which can help in predicting the density of rubber-soils for geomaterials similar to the ones used in this research.
- The chip density is not very sensitive to the size of chips. However, a trend of increasing density with increasing chip size is found, except in the case of vibratory method. In this case the maximum density decreases with increasing chip sizes.

CHAPTER 5

COMPRESSIBILITY

5.1 Introduction

A solution to enhance the stability and reduce the settlement of highway structures on slopes and highly compressible soils is to replace the existing material with a material of lower unit weight and/or use lighter weight fills. Based on the research conducted by the author (see Ahmed 1992; and Ahmed and Lovell, 1992c) and that reported in the literature (see Ahmed, 1991 & 1993 and Chapters 2 & 3), it is found that the use of shredded tires in highway construction as lightweight geomaterial offers technical, environmental, and economic benefits under certain conditions. The most important benefit of using tire chips is reduced weight of fill, which helps increase stability, reduce settlements, reduce backfill pressure on retaining structures, and correct or prevent slides on slopes. However, a major concern in using tire chips in highway structures is the large compressibility of chips observed in various field and laboratory studies (Ahmed, 1992)

Holtz (1989) reports that little information is available on tolerable settlements of highway embankments. However, it has been documented (NCHRP, 1971) that post-construction settlements during the economic life of a roadway of as much as 1 to 2 ft are generally considered tolerable provided they: (a) are reasonably uniform; (b) do not occur adjacent to a pile-supported structure; and (c) occur slowly over a long period of time. To determine the feasibility of tire chips as lightweight embankment fill material, it is considered imperative to fully understand the compressibility behavior of tire chips under different loading conditions.

This chapter presents and evaluates the results from compressibility testing of rubber-soils. Subsequent subsections give: a description of testing equipment and procedures; an outline of the testing program; and presentation of results in graphical and tabulated forms. Also presented is a discussion on the compression behavior of rubber-soils and the compressibility parameters. Finally, salient conclusions are listed.

5.2 Testing Equipment

The compressibility equipment routinely used by geotechnical engineers for fine and coarse grained soils could not be used for this research due to the large size of tire chips and their high compressibility. A large size custom-designed apparatus was built for this purpose. It consisted of: a stainless steel compression mold of 12-in. diameter, 12.5-in. high, and having 0.4-in. wall thickness; and a 1.25 in. thick, 16-inch square stainless steel base plate, with two vertical rods embedded in the plate, for providing a level base and for holding the mold firmly in position during impact compaction (see Figure 5.1). The compression mold was built in a manner to allow it to split into two halves of 12-inch diameter and 6.5/6-inch height, which provided the flexibility of testing rubber-soil samples of 6-inch or even lesser height in order to minimize the error due to side friction (see Figure 5.2). A steel plate, with thickness varying from 1.5 inch in the middle to 1 inch at the edges, was used as a cover plate for the compression mold. The MTS soil testing system, with loading frame adequately modified to accommodate the large size compression mold, was used to apply the loads under simulated field conditions and measure the load-deformation response of rubber-soils (see Figures 5.3 and 5.4).

5.3 Testing Procedures

The tire chips of sizes varying from 0.5-in. to less than 2-in. and two types of soils, i.e., Ottawa sand and Crosby till (see Chapter 4 for the gradation curves of various chip sizes and engineering properties of testing materials) were tested for determining the compressibility

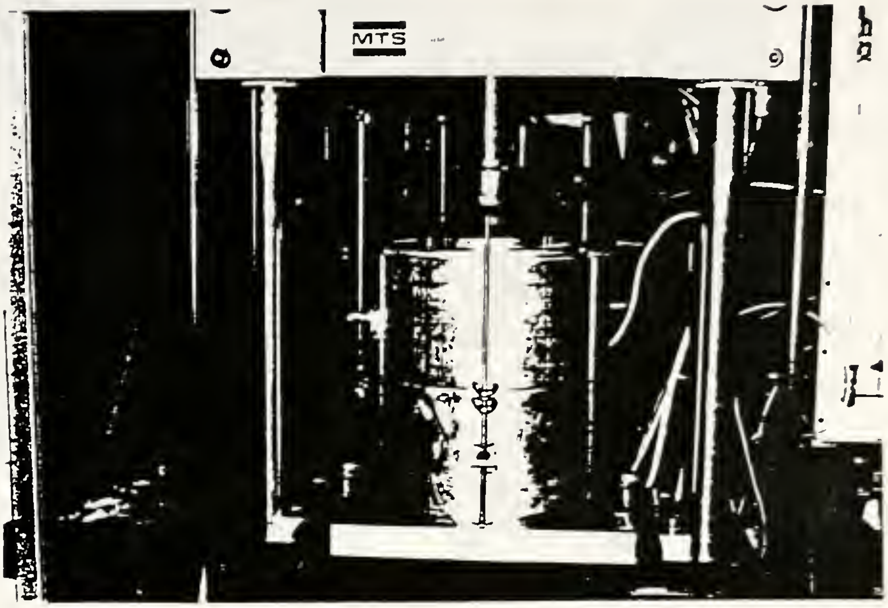


Figure 5.1 A 12-inch diameter compression mold

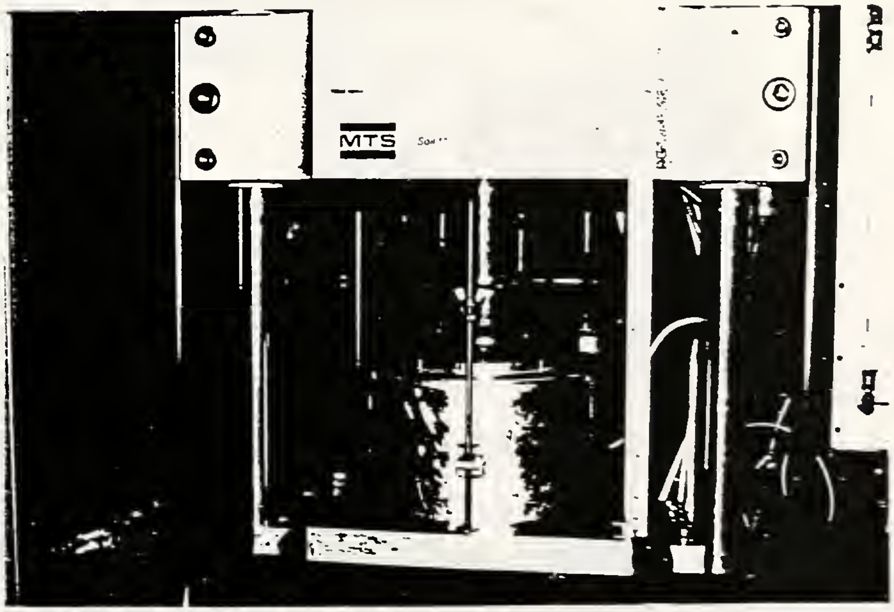


Figure 5.2 Half-size, 12-inch diameter compression mold

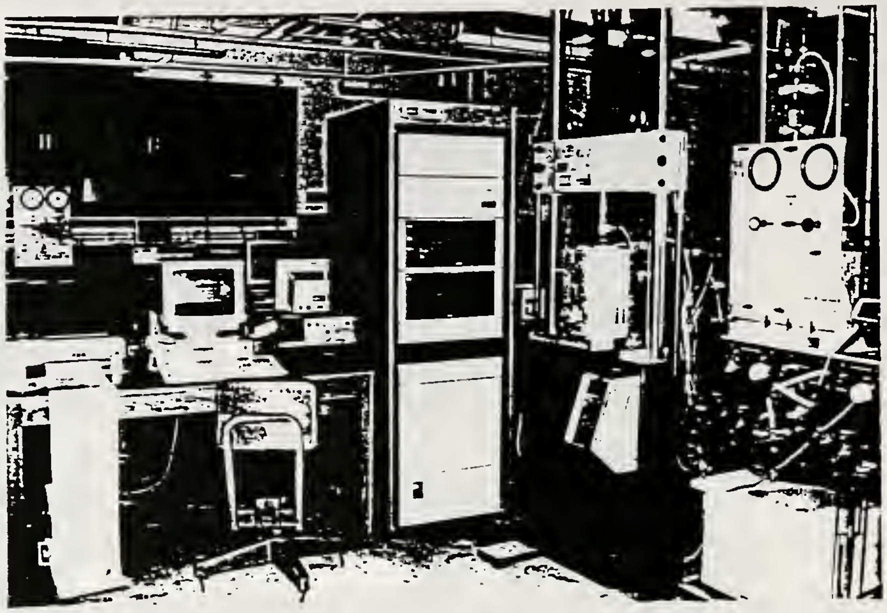


Figure 5.3 The MTS Soil Testing System, with large size compression mold

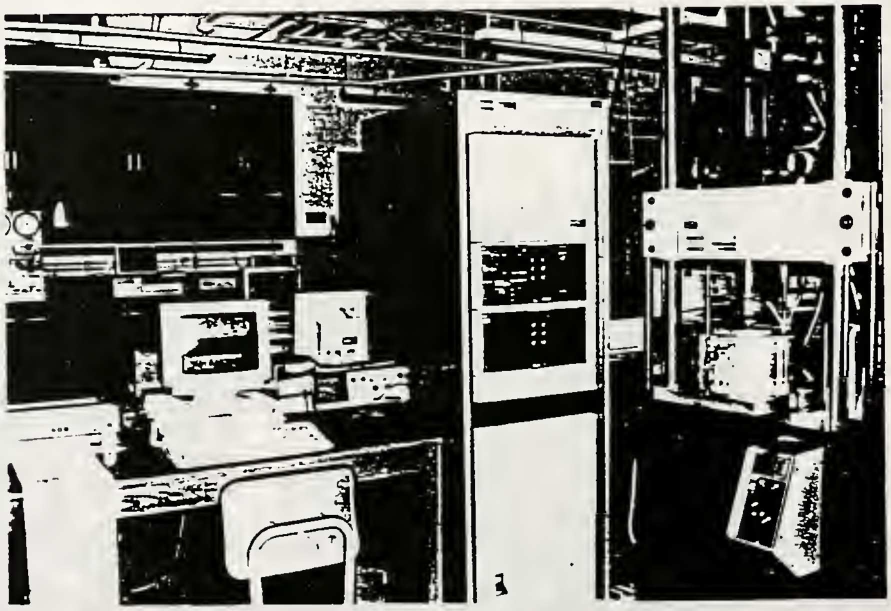


Figure 5.4 The MTS Soil Testing System, with half-size compression mold

behavior of rubber-soils. The samples of tire chips, alone and in a chip-Crosby mix, were compacted manually in 8 layers using a 10-lb hammer with 18-in. drop. Three different compactive efforts were used: 1) energy equivalent to modified Proctor - 368 blows per layer, total of 2944 blows/sample (56,250 ft-lb/ft^3); standard Proctor - 81 blows per layer, total of 648 blows/sample (12,375 ft-lb/ft^3), and 50% of standard Proctor - 40 blows per layer, total of 320 blows/sample (6188 ft-lb/ft^3). Tests were also performed on uncompacted tire chip samples. The specimens of chip-sand mix were compacted using an electromagnet, vertically vibrating table. The samples were vibrated for 8 minutes at 60 Hz. under 2 psi surcharge load (see Chapter 4 for sample preparation procedure using vibratory compaction).

For compression testing, the prepared sample is weighed and the sample height is measured with a micrometer. The test sample is then assembled in the loading frame of the MTS Soil Testing System and a seating load is applied to it. At this stage the load cell and LVDT (acronym for Linearly Varying Differential Transducer) zeroes are recorded. The requisite loads are applied in a stress control mode in a manner which closely simulates field loading conditions.

The stress levels and the loading sequence were selected keeping in view the research objectives set forth in Chapter one. The samples of tire chips alone were subjected to four load/ unload cycles. The samples of rubber-soils were subjected to three load/unload cycles. The loads were applied incrementally using a load increment ratio of one. For the first two cycles, the samples were loaded to a maximum stress of about 25 psi, which is equivalent to approximately 25 ft of soil fill, and then unloaded to a seating load of 0.12 psi. For the third cycle, the samples were loaded to about 15 psi and then unloaded to one psi. Finally, in the fourth cycle, the samples were reloaded to the maximum stress and then completely unloaded. At the end of the fourth cycle, the final height was measured before terminating the test.

5.4 Testing Program

The compressibility testing was done in three stages: 1) testing of chips alone; 2) testing of rubber-sand mix; and 3) testing of rubber-Crosby mix. In the first stage, tire chips of sizes varying from 0.5-inch to 2-inch were tested. The specimens were prepared using three different compactive efforts and also in a loose state (i.e., no compaction). The rubber-sand mix was tested in a dry state and the specimens were prepared using vibratory compaction procedures. In the case of rubber-Crosby, the mix was prepared at optimum moisture content and specimens were prepared using impact energy equivalent to the standard Proctor test. The chip sizes were varied from 0.50 to 2 inch. In rubber-soils mixes, the percent of tire chips was varied from no chips to 100% chips.

5.5 Presentation of Results

The compression curves from tests on pure chips, rubber-sand and rubber-Crosby are compared using vertical strain versus logarithm of vertical stress plots, as follows:

- Figures 5.5 to 5.8 - compression curves for four load/unload cycles from tests on different chip sizes.
- Figures 5.9 to 5.12 - curves for four load/unload cycles from tests on 1-inch chips compacted using different compaction efforts.
- Figures 5.13 to 5.16 - comparative curves for four load/unload cycles from tests on 2-inch chips compacted using different efforts.
- Figures 5.17 to 5.20 - comparison tests from different chip sizes and compactive efforts for four load/unload cycles.
- Figures 5.21 to 5.23 - comparison of compression curves from testing of rubber-sand with variable chip/mix ratios.
- Figures 5.24 to 5.26 - curves from different load/unload cycles of 2-inch chips/Crosby mix, having variable chip/mix ratios.

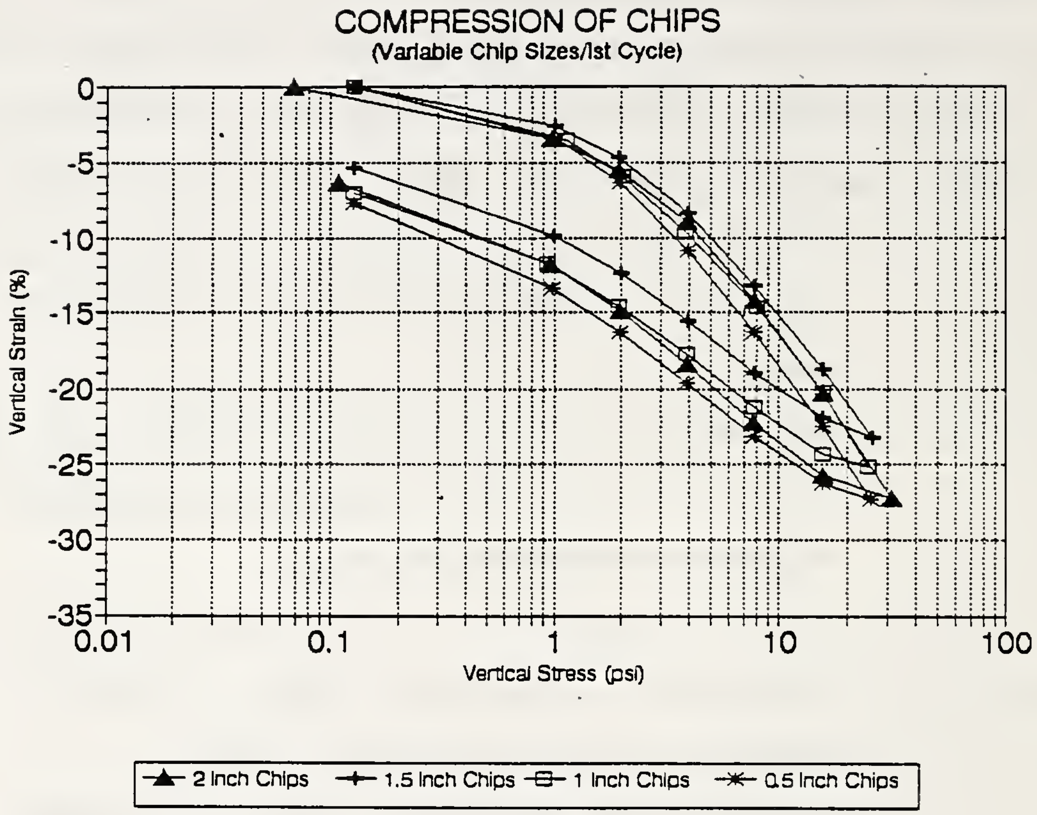


Figure 5.5 Compression curves for variable chip sizes-Ist cycle

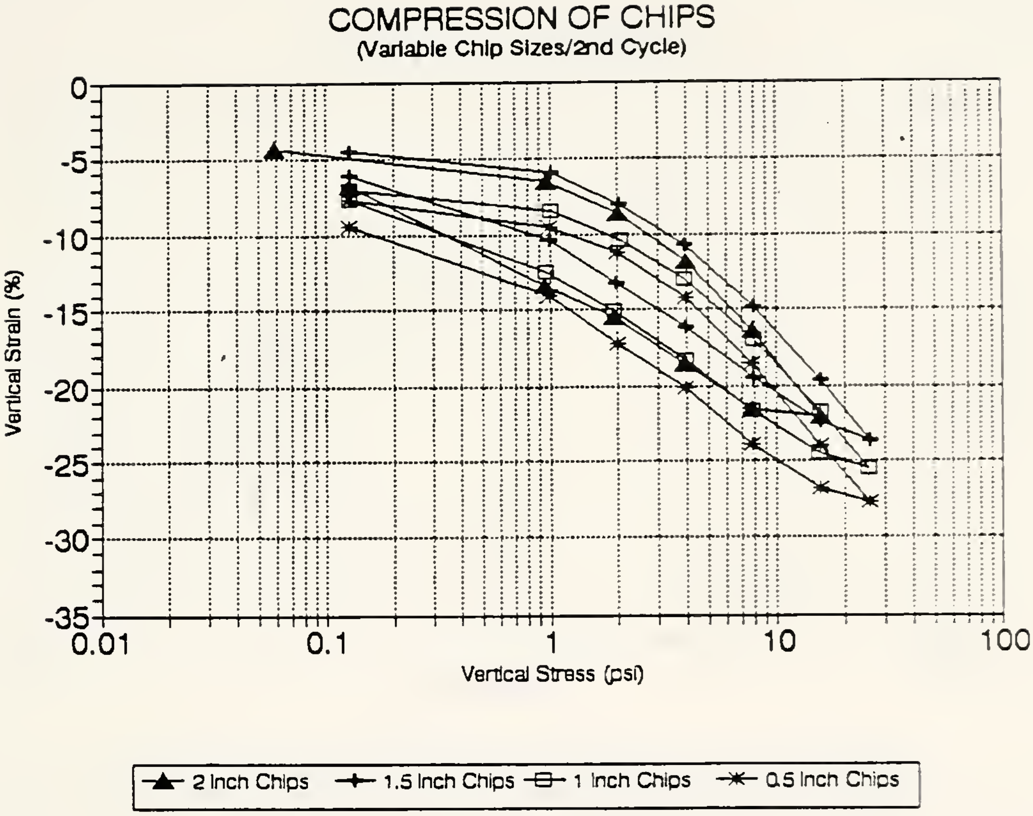


Figure 5.6 Compression curves for variable chip sizes - 2nd cycle

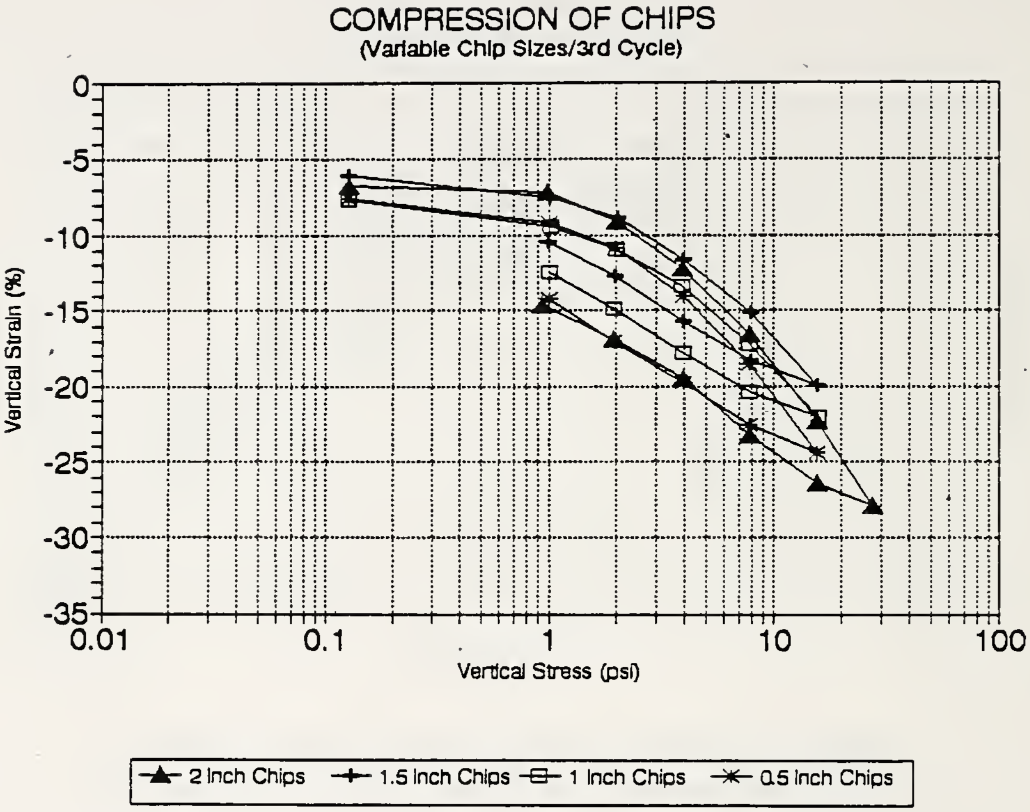


Figure 5.7 Compression curves for variable chip sizes - 3rd cycle

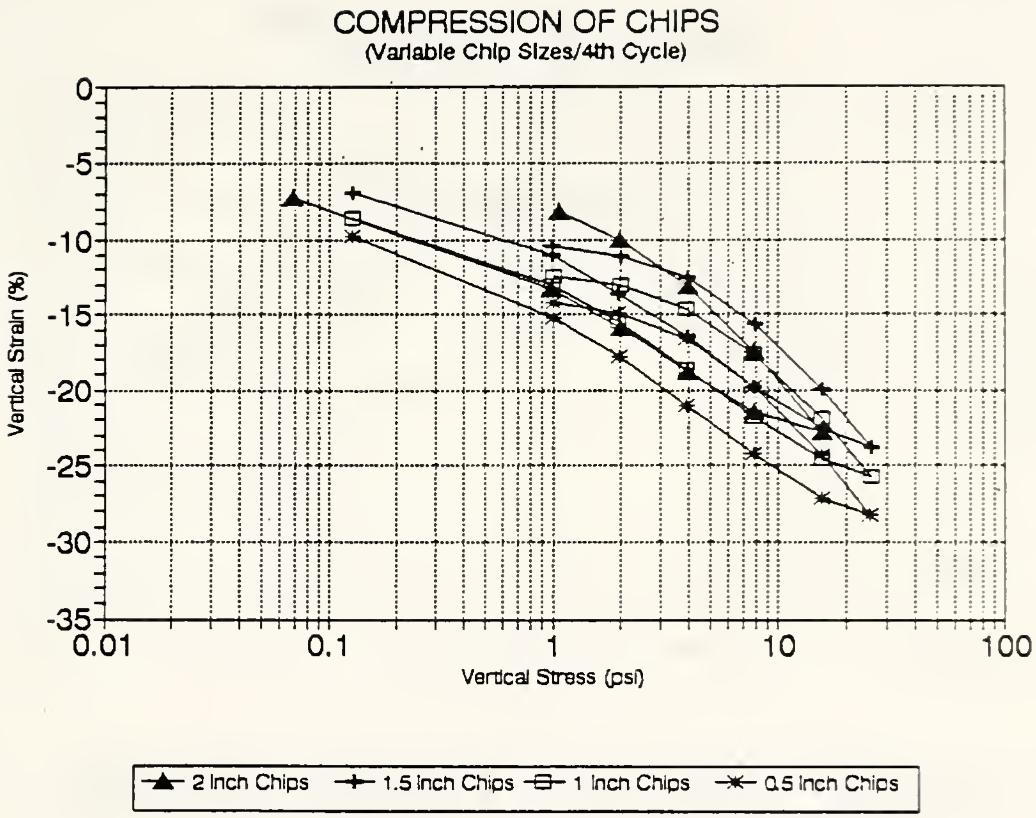


Figure 5.8 Compression curves for variable chip sizes - 4th cycle

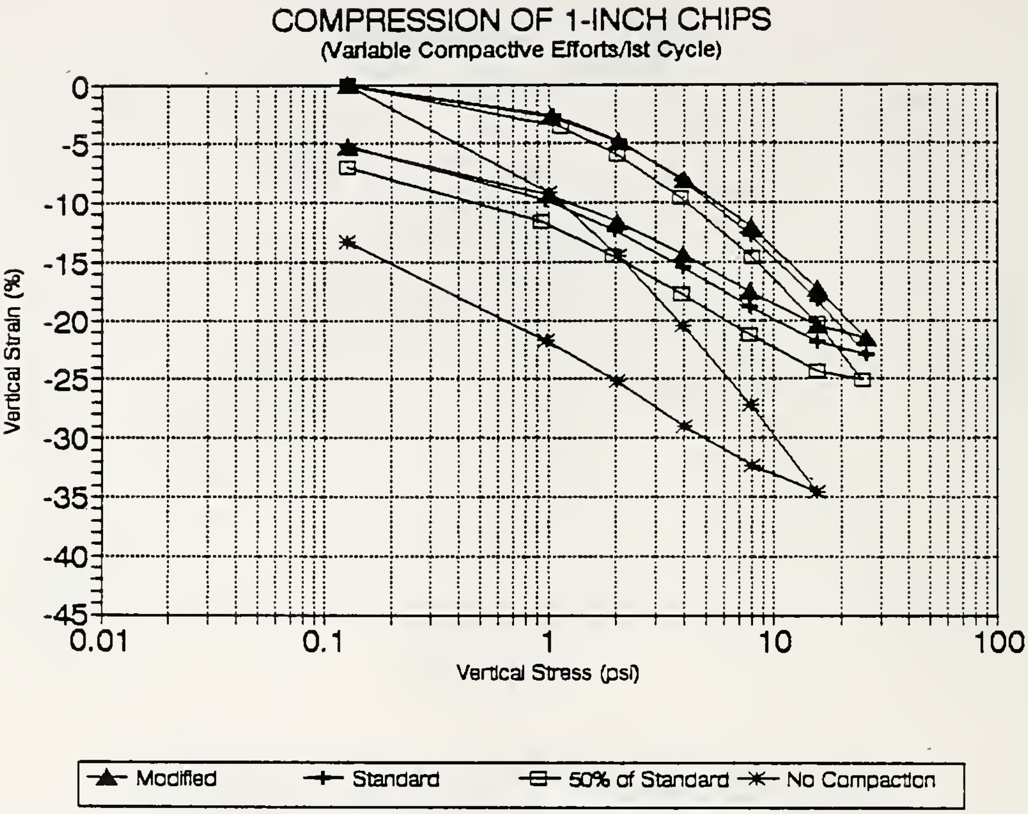


Figure 5.9 Compression curves for 1-inch chips with variable compactive effort - Ist cycle

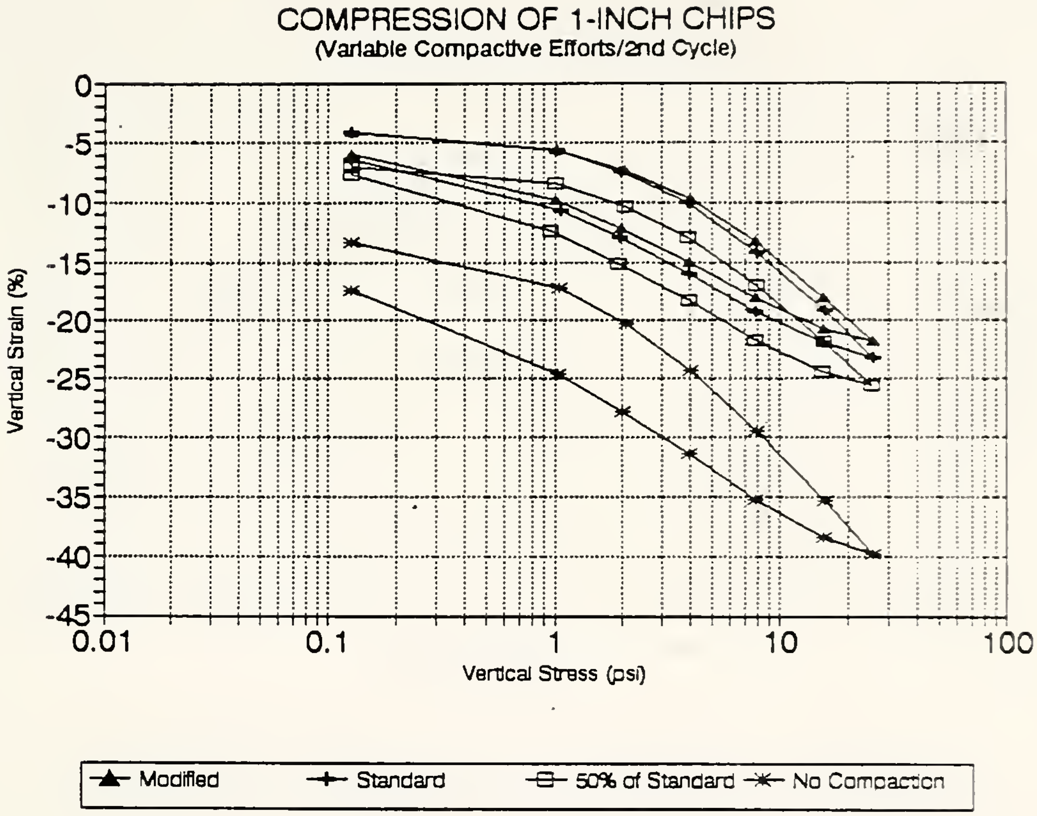


Figure 5.10 Compression curves for 1-inch chips with variable compactive effort - 2nd cycle

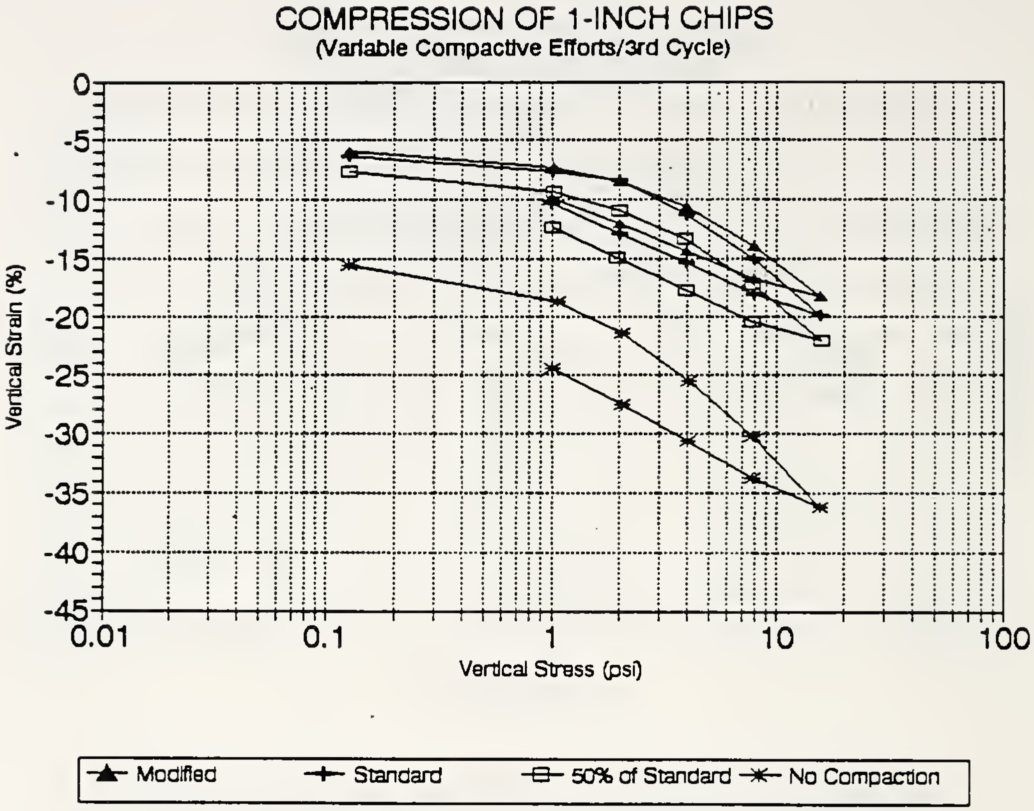


Figure 5.11 Compression curves for 1-inch chips with variable compactive effort - 3rd cycle

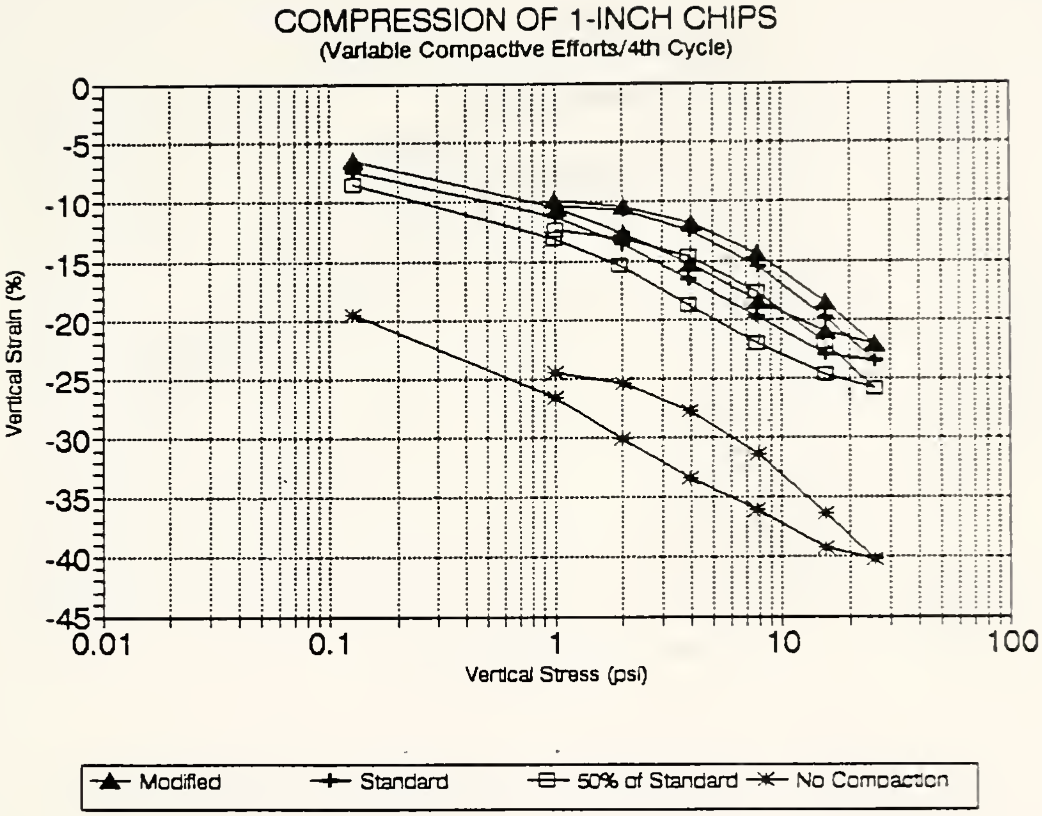


Figure 5.12 Compression curves for 1-inch chips with variable compactive effort - 4th cycle

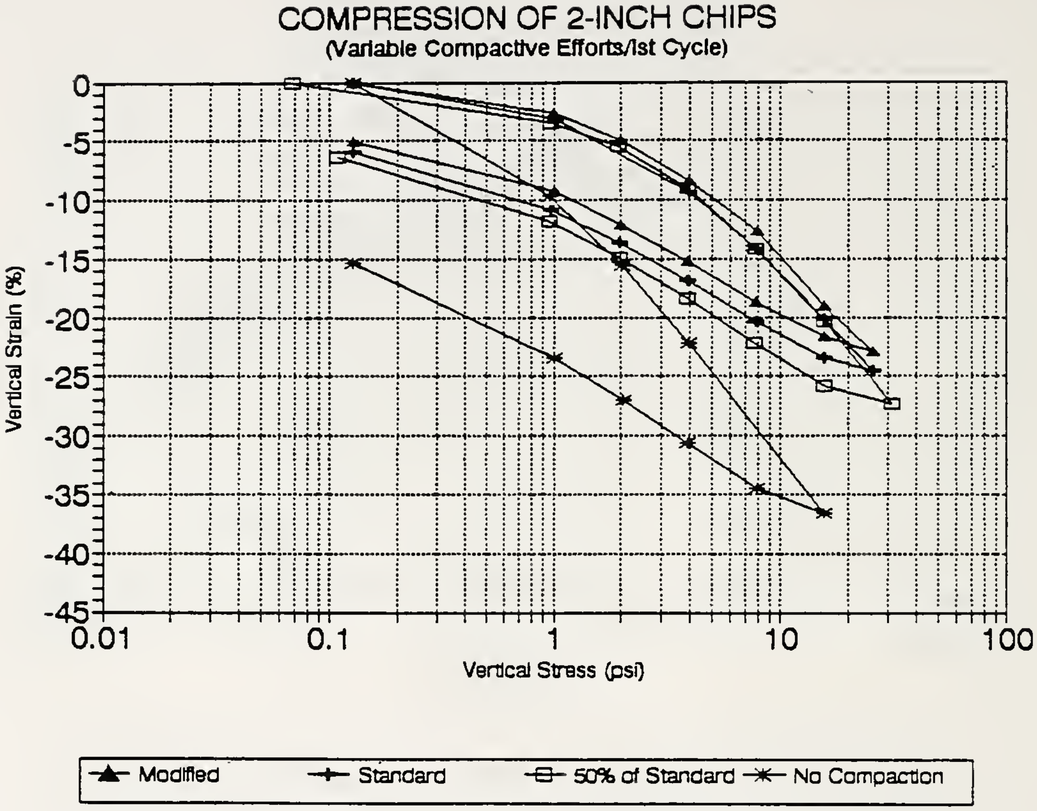


Figure 5.13 Compression curves for 2-inch chips with variable compactive effort - Ist cycle

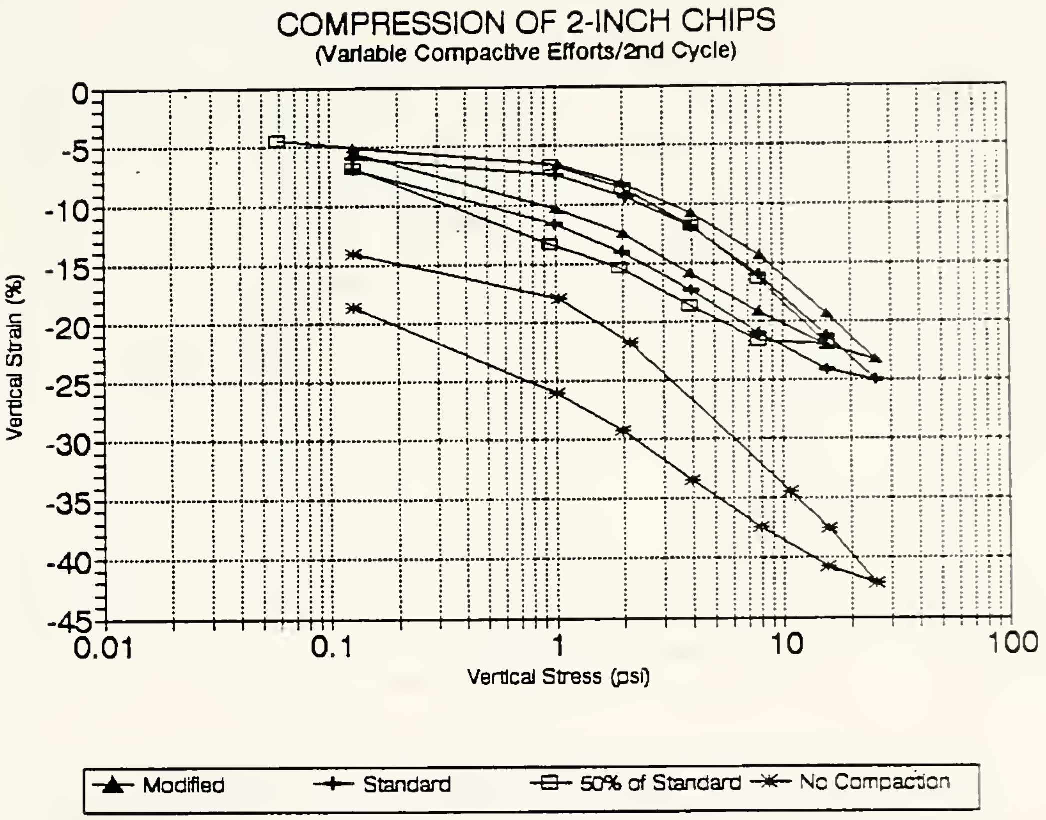


Figure 5.14 Compression curves for 2-inch chips with variable compactive effort - 2nd cycle

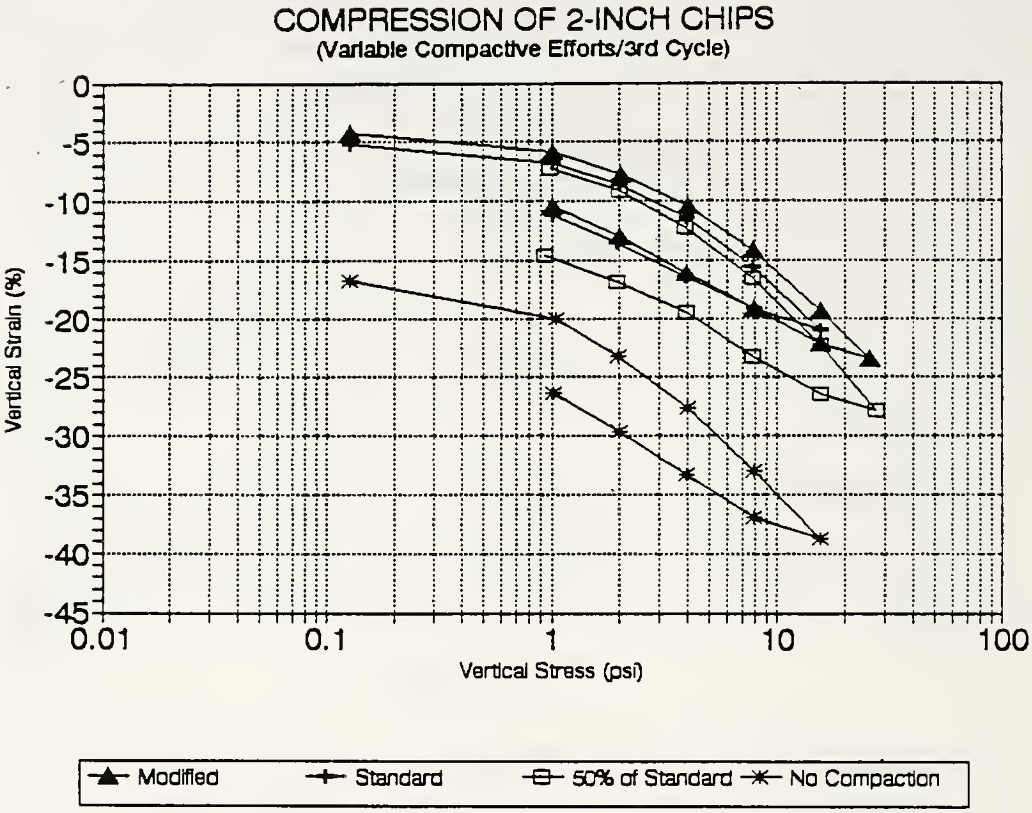


Figure 5.15 Compression curves for 2-inch chips with variable compactive effort - 3rd cycle

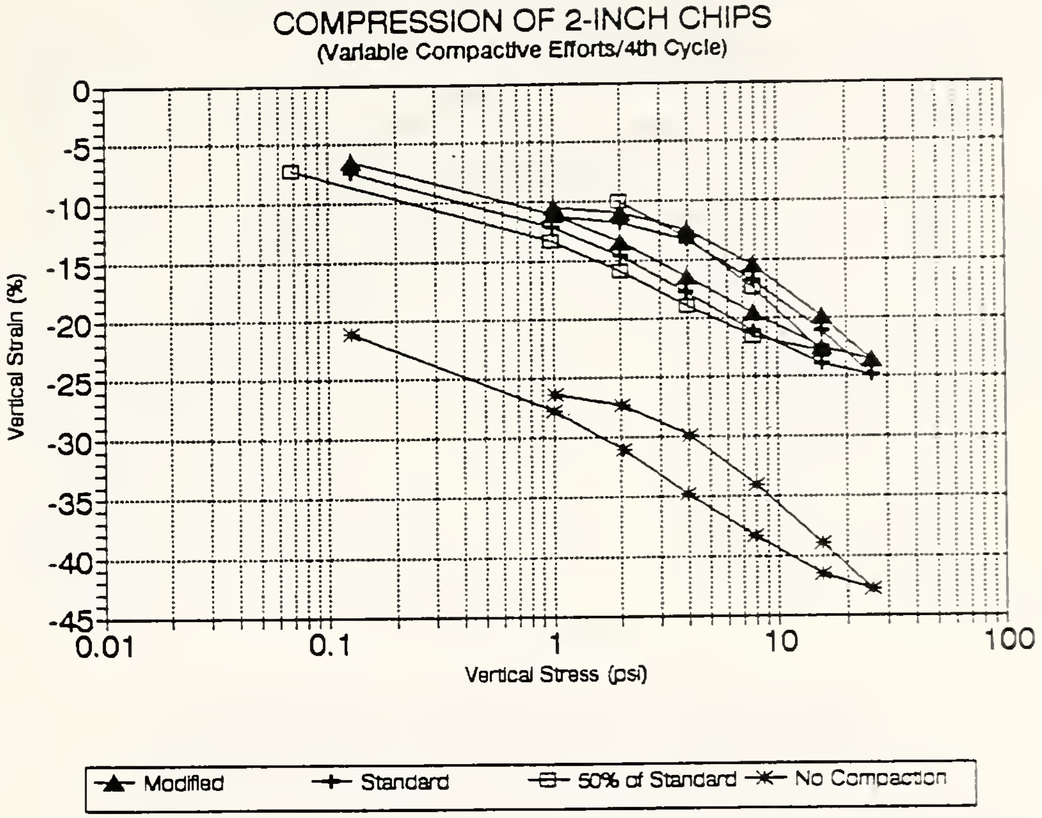


Figure 5.16 Compression curves for 2-inch chips with variable compactive effort - 4th cycle

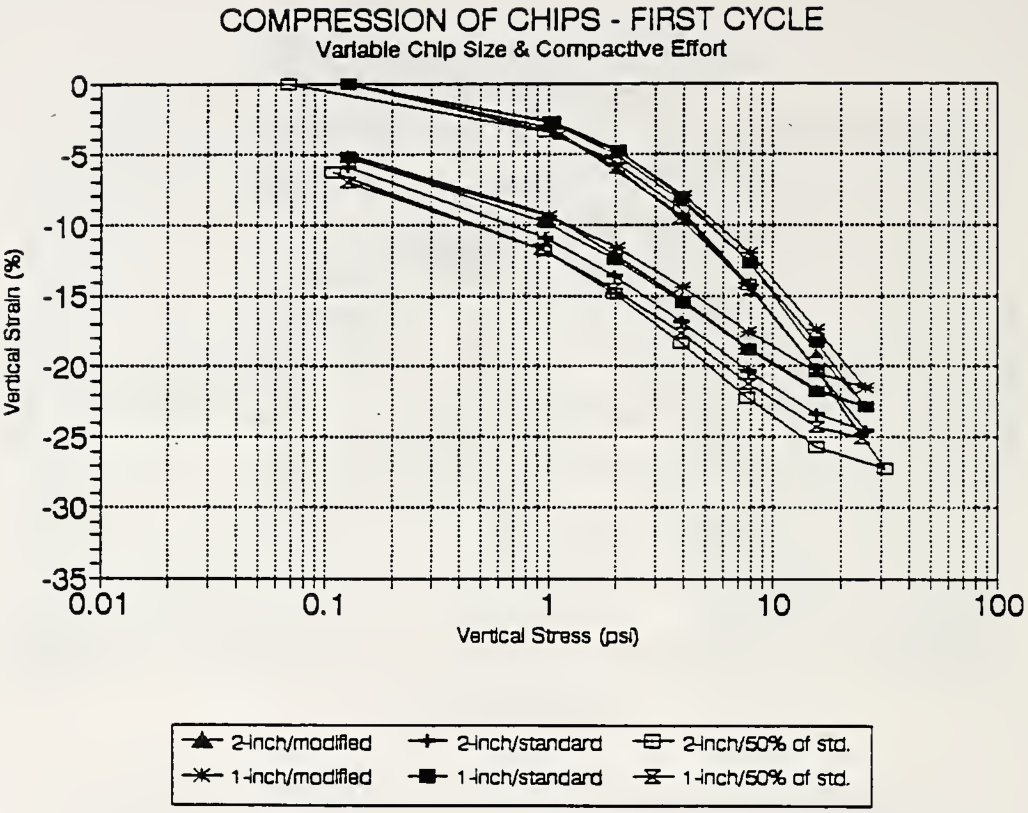


Figure 5.17 Comparison of compression curves with variable chip sizes and compactive effort - Ist cycle

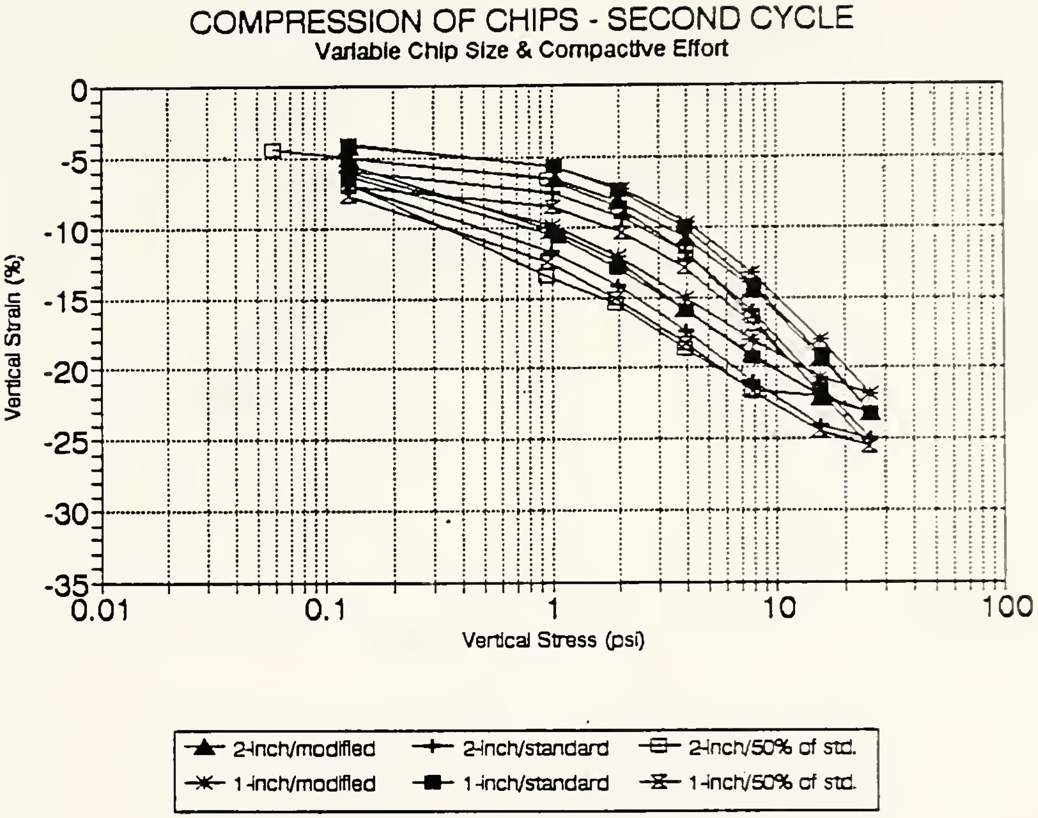


Figure 5.18 Comparison of compression curves with variable chip sizes and compactive effort - 2nd cycle

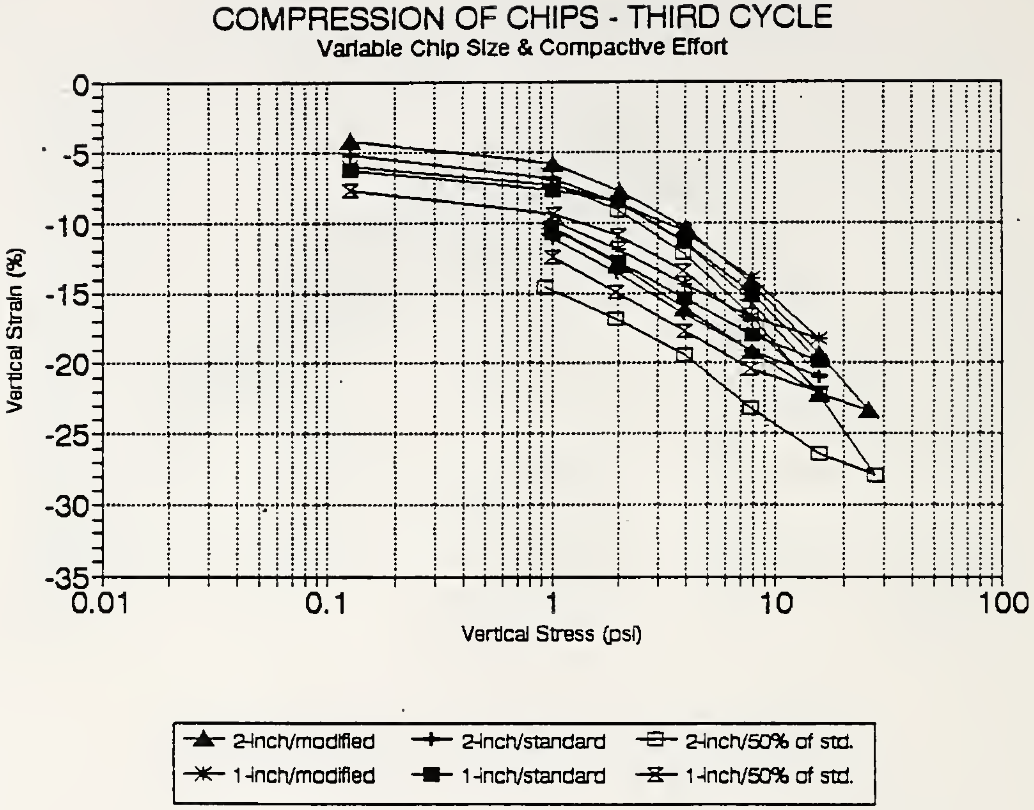


Figure 5.19 Comparison of compression curves with variable chip sizes and compactive effort - 3rd cycle

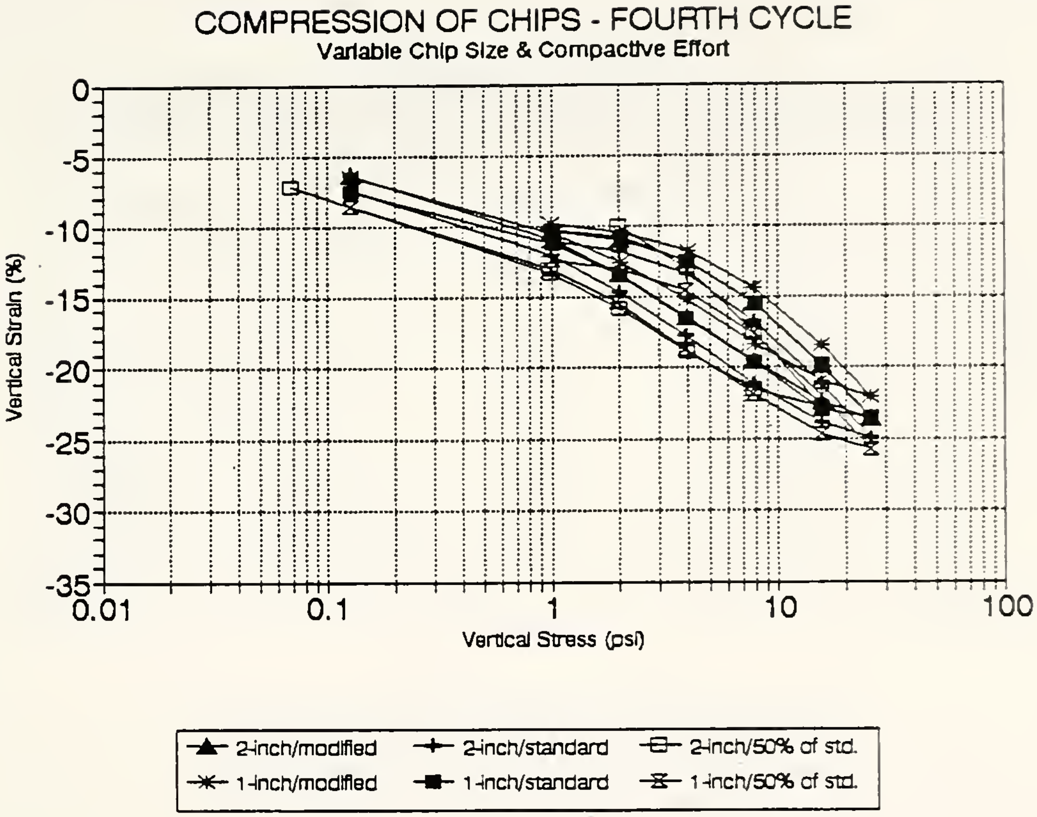


Figure 5.20 Comparison of compression curves with variable chip sizes and compactive effort - 4th cycle

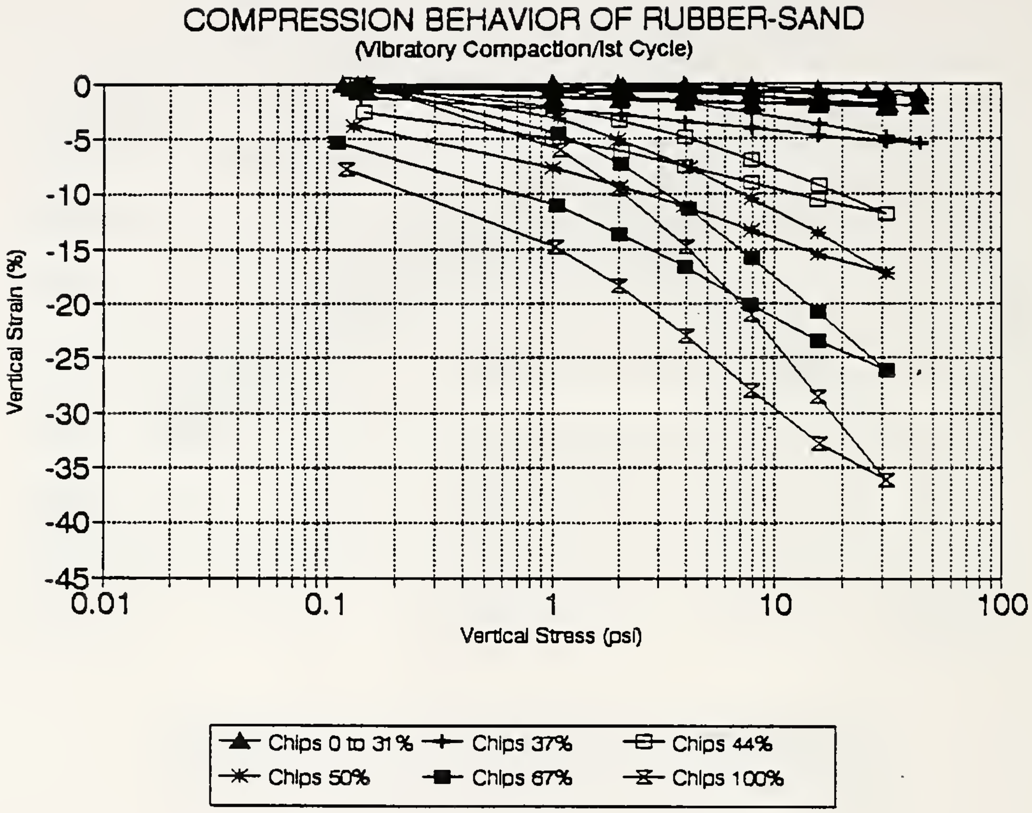


Figure 5.21 Compression behavior of rubber-sand with variable chip/mix ratios -Ist cycle

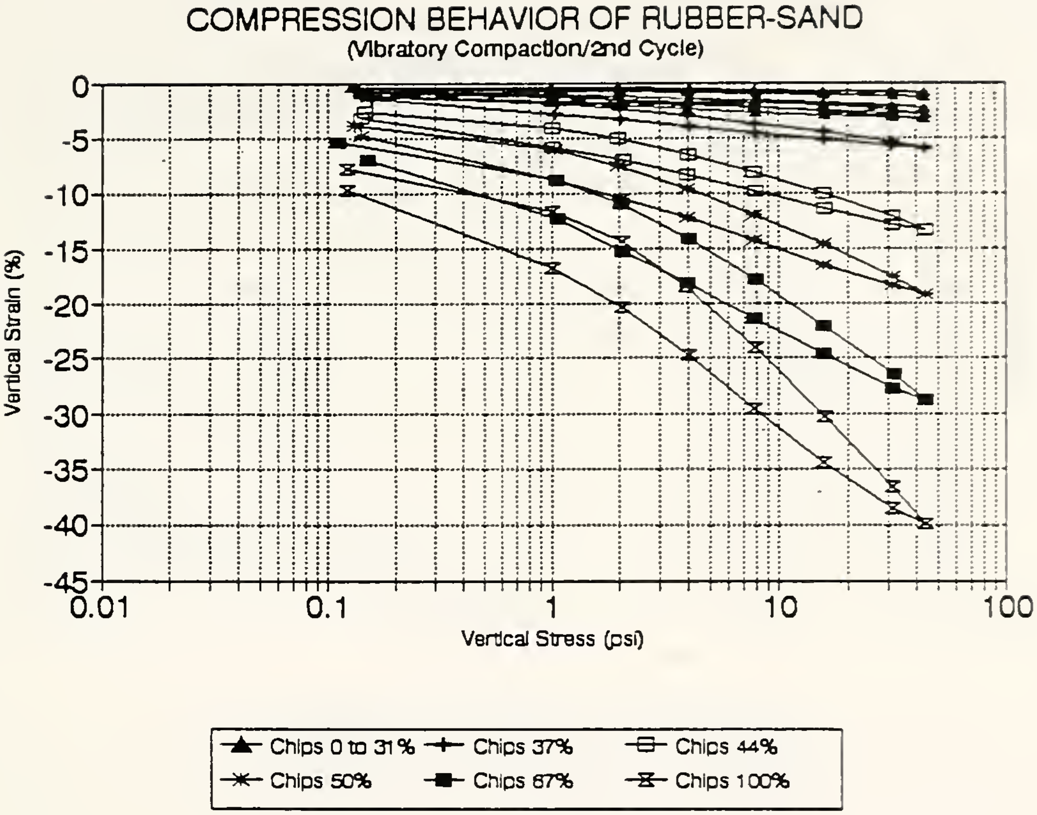


Figure 5.22 Compression behavior of rubber-sand with variable chip/mix ratios -2nd cycle

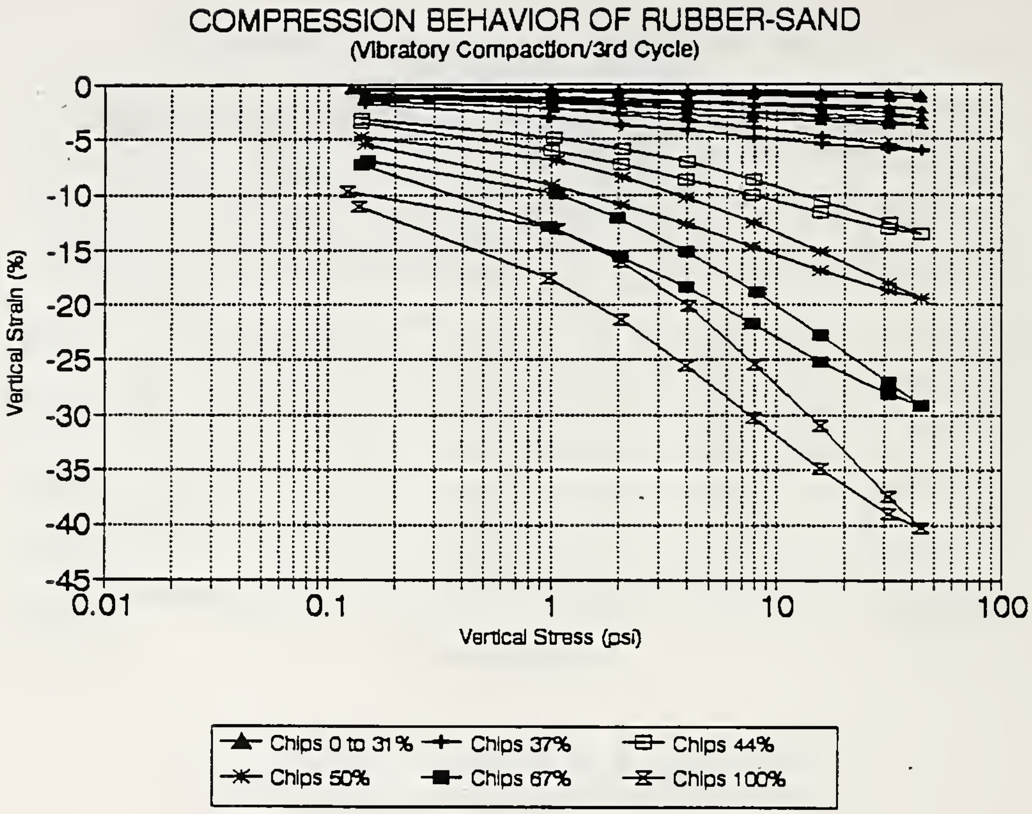


Figure 5.23 Compression behavior of rubber-sand with variable chip/mix ratios -3rd cycle

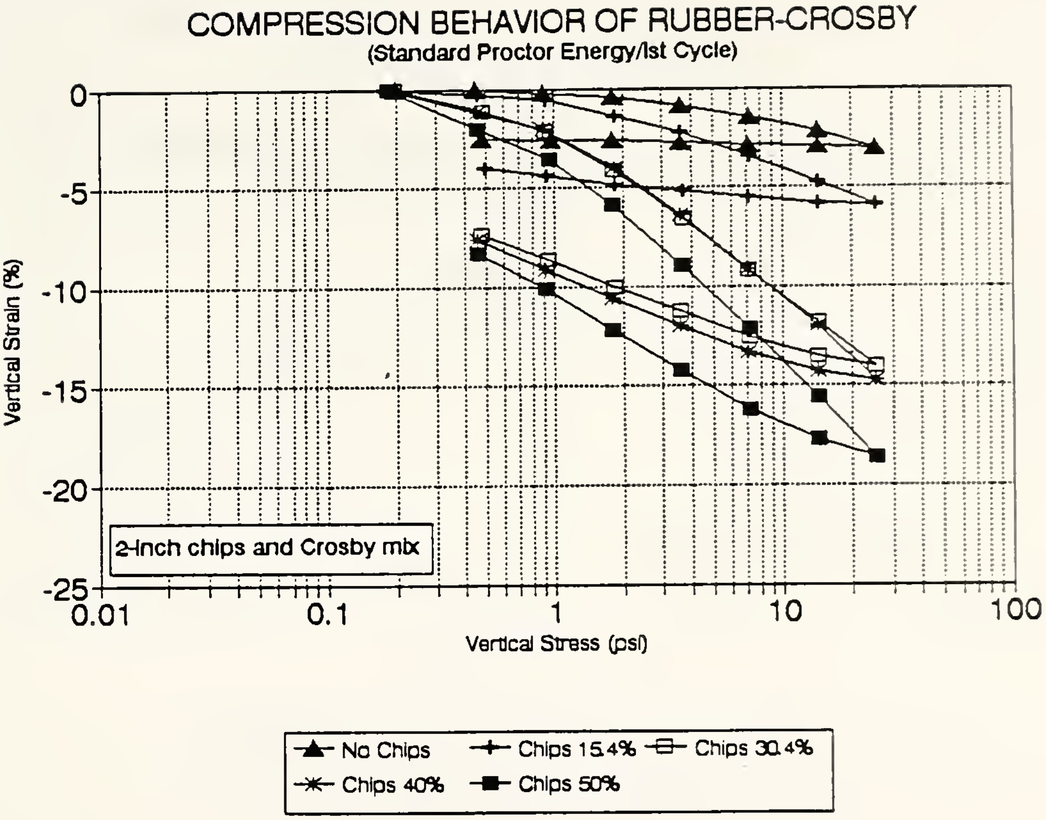


Figure 5.24 Compression behavior of rubber-Crosby till with variable chip/mix ratios - Ist cycle

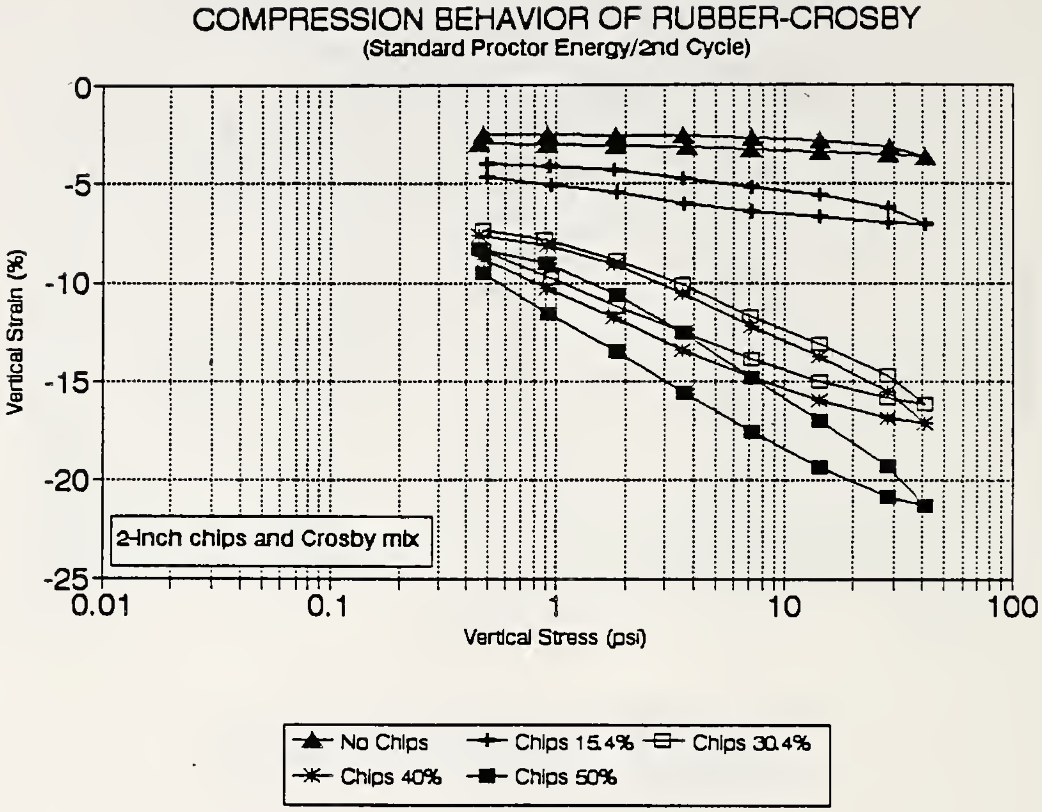


Figure 5.25 Compression behavior of rubber-Crosby till with variable chip/mix ratios - 2nd cycle

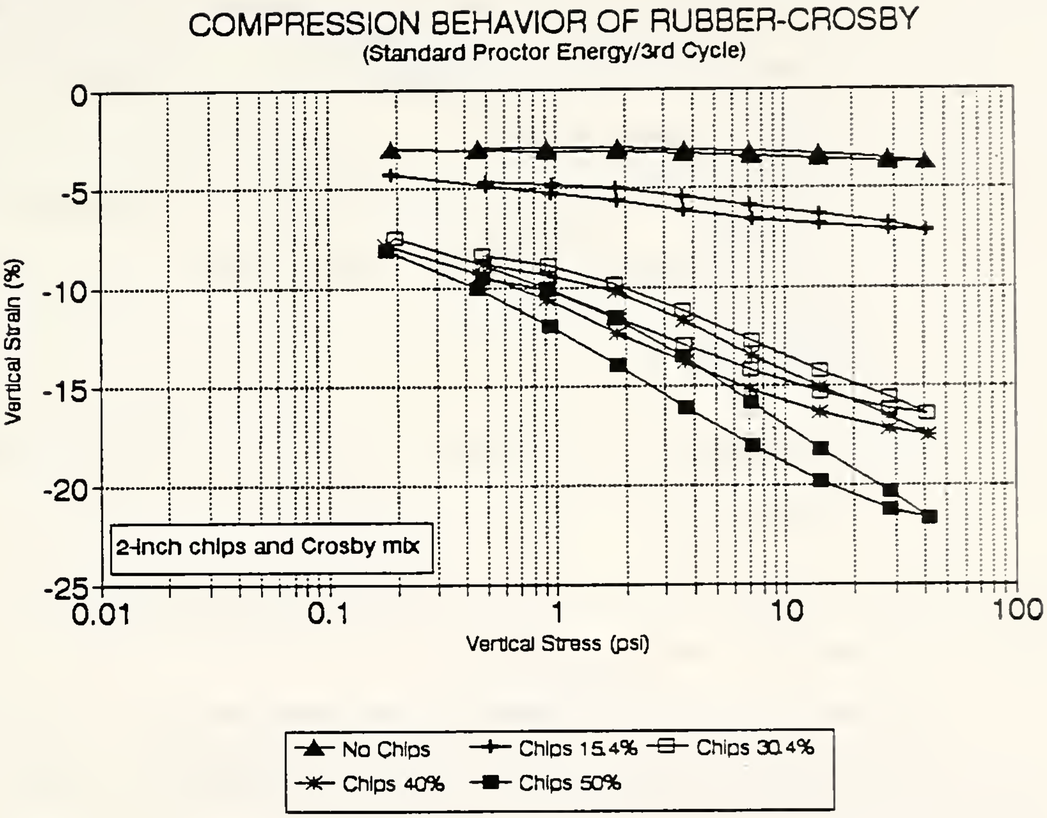


Figure 5.26 Compression behavior of rubber-Crosby till with variable chip/mix ratios - 3rd cycle

- Figures 5.27 to 5.29 - comparison of the effect of variable chip sizes on the behavior of rubber-soils, at an optimum chip/mix ratio.
- Tables 5.1 to 5.3 - comparative vertical strains at an average stress of 10 and 20 psi from tests on tire chips, rubber-sand, rubber-Crosby, respectively.
- Tables 5.4 to 5.6 - a summary of compressibility parameters for chips, rubber-sand, and rubber-Crosby mixes.
- Table 5.7 - compares the results of compressibility testing of tire chips, rubber-sand, and rubber-Crosby.

5.6 Discussion

Figures 5.5 to 5.8 compare the compression curves for four load/unload cycles from tests on four different chip sizes varying from 0.5 to 2-inch. The curves from different chip sizes have similar shapes and show little variation in vertical strains at different stress levels, indicating that variation in chip sizes does not significantly effect the compression behavior of tire chips. The results from 1 and 2-inch chip sizes are almost identical, while the results from 0.5-inch chip size show comparatively larger vertical strains, with maximum differences reaching about 4% at 20 psi. The 1.50-inch chips show the least strains at

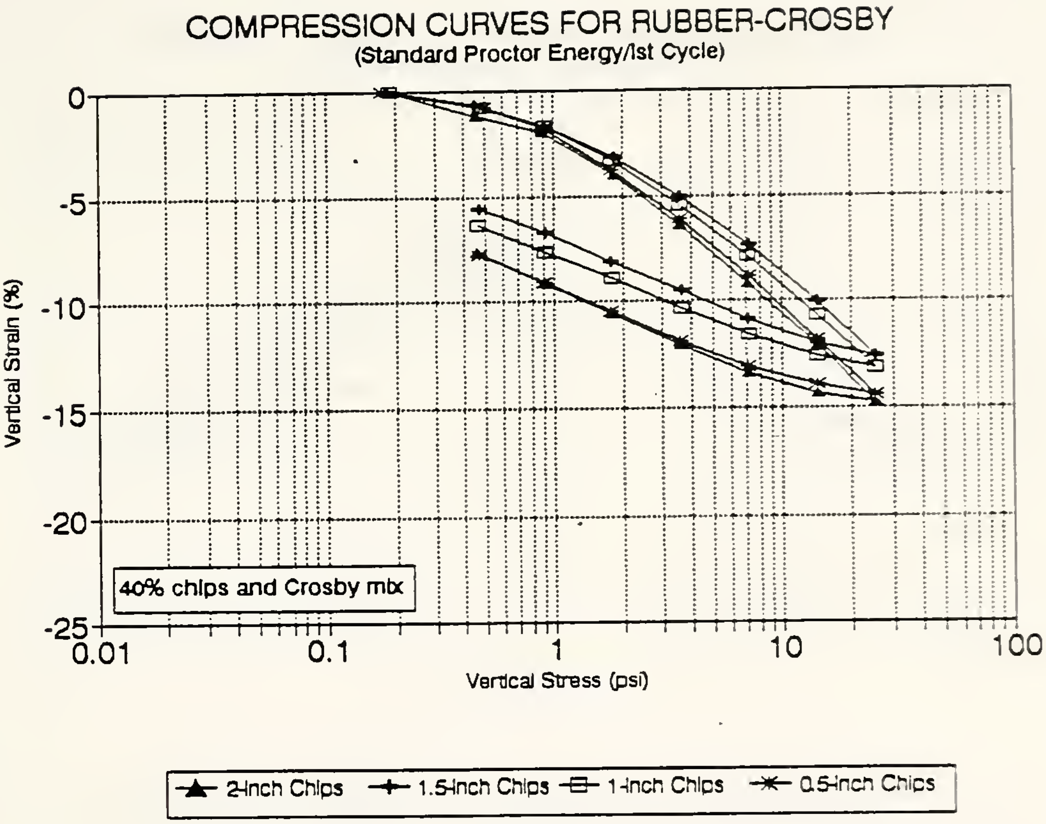


Figure 5.27 Compression behavior of rubber-Crosby till with variable chip sizes - Ist cycle

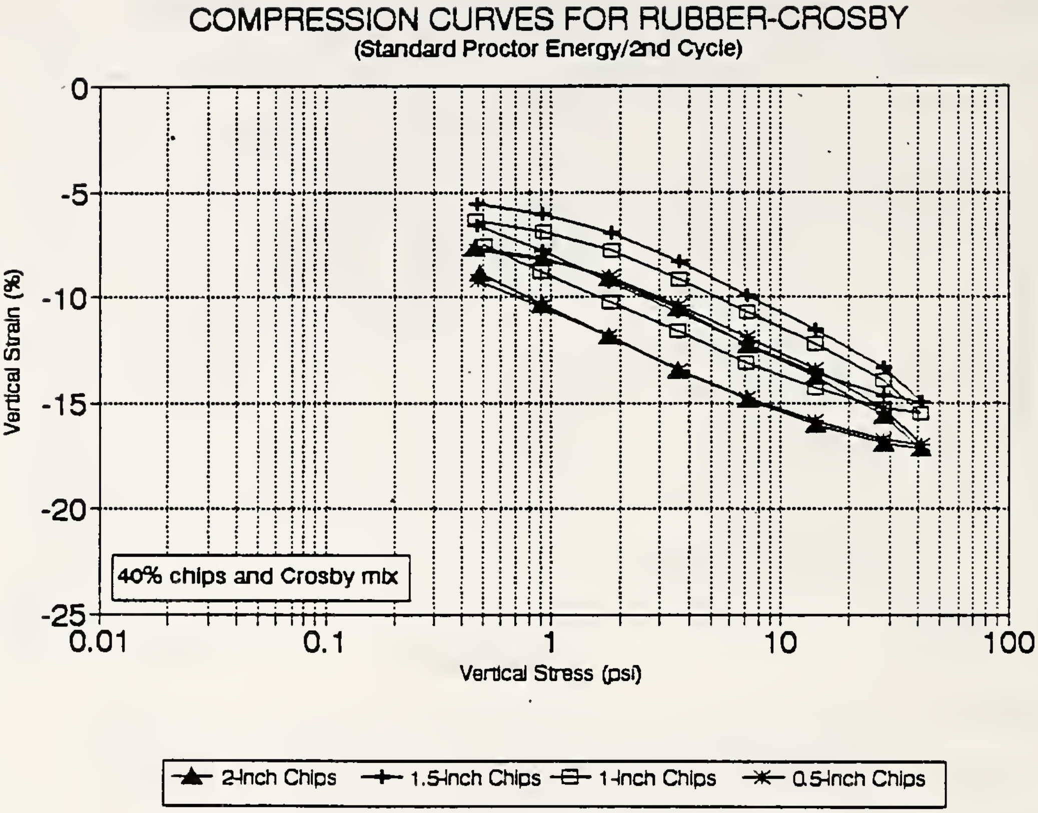


Figure 5.28 Compression behavior of rubber-Crosby till with variable chip sizes- 2nd cycle

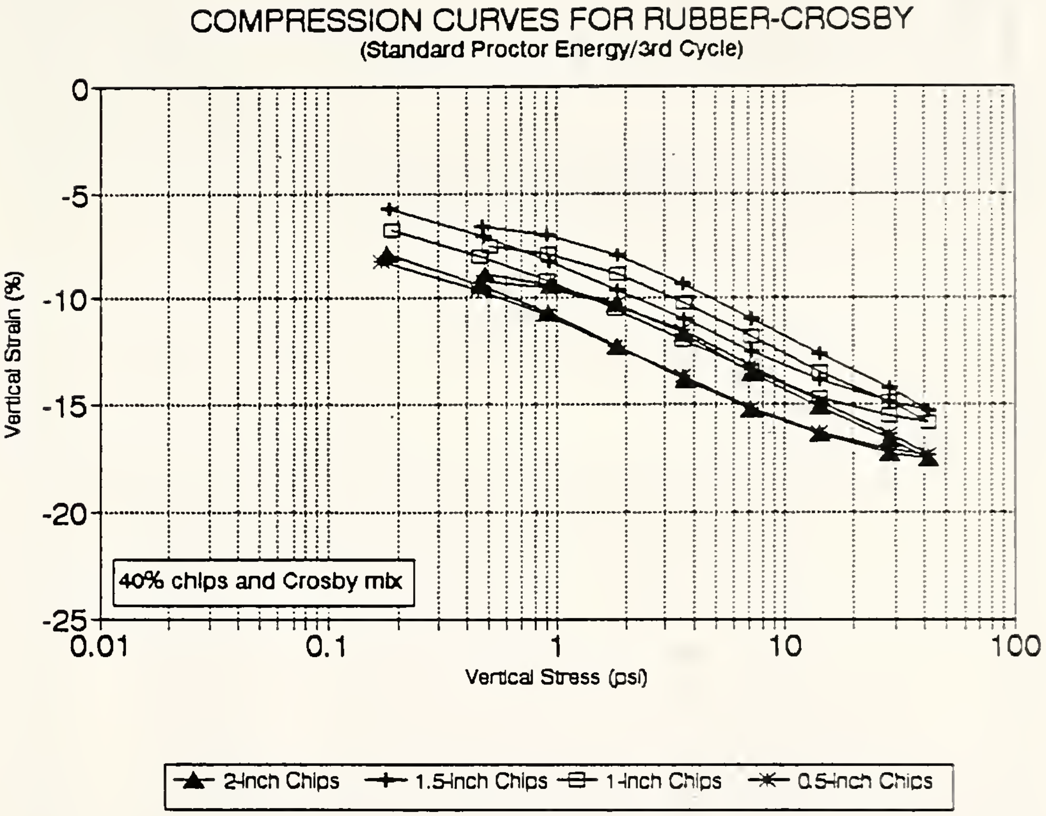


Figure 5.29 Compression behavior of rubber-Crosby till with variable chip sizes - 3rd cycle

Table 5.1 Comparison of vertical strains from tests on tire chips

Test no	Chip Size (in)	Compactive Effort	Dry density (pcf)	Vertical Strain (%) σ_v = 10 psi	Vertical Strain (%) σ_v = 20 psi
CTC 01	2.0	50% Standard	38.33	16.25	22.50
CTC 02	1.5	50% Standard	40.25	15.25	20.50
CTC 03	1.0	50% Standard	39.57	16.00	22.00
CTC 04	0.5	50% Standard	38.99	18.50	25.00
CTC 05	2.0	Standard	39.62	16.25	22.25
CTC 06	1.0	Standard	40.95	15.00	20.50
CTC 07	2.0	Modified	41.71	15.00	20.75
CTC 08	1.0	Modified	42.50	13.50	19.25
CTC 09	2.0	No Compaction	29.08	31.90	39.90
CTC 10	1.0	No Compaction	30.50	30.00	37.50

Mean ± 1 Standard Deviation = 15.72 ± 1.349 21.59 ± 1.690

Notes: 1. Modified = Modified Proctor Energy = 56.250 $ft\text{-}lb/ft^3$
2. Standard = Standard Proctor Energy = 12.375 $ft\text{-}lb/ft^3$
3. 50% Standard = 50% Standard Proctor Energy = 6.188 $ft\text{-}lb/ft^3$

Table 5.2 Comparison of vertical strains from tests on rubber-sand mix

Test no.	Chip Size (in)	Chips Ratio (%)	Dry density (pcf)	Vertical Strain (%)	
				σ_v = 10 psi	σ_v = 20 psi
CTRS01	1.0	0.0	116.3	0.36	0.56
CTRS02	1.0	9.1	109.4	0.61	0.82
CTRS03	1.0	16.7	103.8	1.21	1.59
CTRS04	1.0	23.1	99.3	1.36	1.83
CTRS05	1.0	31.3	91.7	1.74	2.29
CTRS06	1.0	37.0	86.1	3.00	4.05
CTRS07	1.0	44.0	73.1	7.71	10.05
CTRS08	1.0	50.0	64.4	11.62	15.10
CTRS09	1.0	66.7	49.7	17.56	25.71
CTRS10	1.0	100.0	32.8	31.05	36.12

Notes: 1. All samples are prepared using vibratory compaction
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent

Table 5.3 Comparison of vertical strains from tests on rubber-Crosby till

Test no.	Chip Size (in)	Chip ratio (%)	Dry density (pcf)	Vertical Strain (%)	
				σ_v = 10 psi	σ_v = 20 psi
CTRC01	No Chip	0.0	119.1	2.11	2.81
CTRC02	2.0	15.4	99.1	4.02	5.36
CTRC03	2.0	30.4	78.3	10.26	13.08
CTRC04	2.0	40.0	71.3	10.62	13.48
CTRC05	2.0	50.0	62.7	13.65	17.26
CTRC06	1.5	39.9	73.9	8.77	11.54
CTRC07	1.0	40.0	72.5	9.33	12.02
CTRC08	0.5	40.0	70.2	10.45	13.23
Mean ± 1 S.D.			71.98 ± 1.377	9.79 ± 0.771	12.57 ± 0.810

Notes:
1. All samples are prepared using Standard Proctor Compactive Energy = 12,375 ft-lb/ft^3
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent
3. Mean and 1 standard deviation is given for tests CTRC04, CTRC06, CTRC07 and CTRC08 only

Table 5.4 Compressibility parameters for tire chips

Test no.	Chip Size (in)	Compactive Effort	Dry density (pcf)	CR for σ_v (psi)			RR for σ_v (psi)		SR for σ_v (psi)
				2-4	4-10	10-20	4-10	10-20	10-1
CTC01	2.0	50% Std.	38.33	0.11	0.18	0.21	0.15	0.19	0.12
CTC02	1.5	50% Std.	40.25	0.12	0.17	0.19	0.14	0.18	0.11
CTC03	1.0	50% Std.	39.57	0.12	0.17	0.20	0.13	0.17	0.11
CTC04	0.5	50% Std.	38.99	0.14	0.19	0.22	0.15	0.18	0.11
CTC05	2.0	Standard	39.62	0.12	0.16	0.20	0.14	0.17	0.11
CTC06	1.0	Standard	40.95	0.12	0.16	0.19	0.13	0.17	0.10
CTC07	2.0	Modified	41.71	0.12	0.16	0.21	0.14	0.19	0.10
CTC08	1.0	Modified	42.50	0.11	0.16	0.18	0.13	0.17	0.10
CTC09	2.0	None	29.08	0.21	0.23	0.25	0.14	0.21	0.14
CTC10	1.0	None	30.50	0.20	0.23	0.25	0.14	0.21	0.13
Mean ± 1 S. D.			40.24 ± 1.314	0.121 ± 0.008	0.169 ±0.011	0.200 ±0.012	0.139 ±0.008	0.178 ±0.008	0.108 ±0.007

Notes:
1. Modified = Modified Proctor Energy = 56,250 ft-lb/ft^3
2. Standard = Standard Proctor Energy = 12,375 ft-lb/ft^3
3. 50% Standard = 50% of Standard Proctor Energy = 6,188 ft-lb/ft^3
4. Mean and one standard deviation (SD) do not include CTC09 and CTC10
5. CR = Compression ratio, slope of ϵ_v vs. $\log(\sigma_v)$ in virgin zone of compression
   RR = Recompression ratio, average slope of ϵ_v vs. $\log(\sigma_v)$ plot for recompression portion of curve
   SR = Swelling ratio, slope of rebound curve

Table 5.5 Compressibility parameters for rubber-sand

Test no.	Chip Size (in)	Chip Ratio (%)	Dry density (pcf)	CR for σ_v (psi)			RR for σ_v (psi)		SR for σ_v (psi)
				2-4	4-10	10-20	4-10	10-20	10-1
CTRS01	1.0	0.0	116.3	0.003	0.005	0.006	0.003	0.004	0.003
CTRS02	1.0	9.1	109.4	0.004	0.006	0.008	0.004	0.005	0.004
CTRS03	1.0	16.7	103.8	0.009	0.010	0.013	0.006	0.008	0.006
CTRS04	1.0	23.1	99.3	0.010	0.014	0.016	0.007	0.012	0.007
CTRS05	1.0	31.3	91.7	0.014	0.016	0.019	0.010	0.015	0.011
CTRS06	1.0	37.0	86.1	0.023	0.029	0.034	0.019	0.028	0.021
CTRS07	1.0	44.0	73.1	0.055	0.069	0.079	0.044	0.064	0.050
CTRS08	1.0	50.0	64.4	0.075	0.101	0.110	0.069	0.073	0.067
CTRS09	1.0	66.7	49.7	0.118	0.151	0.179	0.118	0.150	0.116
CTRS10	1.0	100.0	32.8	0.175	0.235	0.259	0.151	0.217	0.153

Notes: 1. All samples are prepared using vibratory compaction
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent
3. CR = Compression ratio, slope of ϵ_v vs. $\log(\sigma_v)$ in virgin zone of compression
RR = Recompression ratio, average slope of ϵ_v vs. $\log(\sigma_v)$ plot for recompression portion of curve
SR = Swelling ratio, slope of rebound curve

Table 5.6 Compressibility parameters for rubber-Crosby till

Test no.	Chip Size (in)	Chip Ratio (%)	Dry density (pcf)	CR for σ_v (psi)		RR for σ_v (psi)		SR for σ_v (psi)
				2-4	4-20	1-5	5-20	10-1
CTRC01	No Chip	0.0	119.1	0.016	0.030	0.003	0.007	0.003
CTRC02	2.0	15.4	99.1	0.032	0.045	0.015	0.017	0.014
CTRC03	2.0	30.4	78.3	0.081	0.090	0.047	0.051	0.045
CTRC04	2.0	40.0	71.3	0.085	0.100	0.051	0.053	0.045
CTRC05	2.0	50.0	62.7	0.101	0.119	0.071	0.072	0.062
CTRC06	1.5	39.9	73.9	0.064	0.090	0.047	0.056	0.045
CTRC07	1.0	40.0	72.5	0.071	0.087	0.046	0.053	0.044
CTRC08	0.5	40.0	70.2	0.077	0.105	0.045	0.056	0.045
Mean ± 1 S.D.			71.98 ± 1.377	0.074 ±0.008	0.096 ±0.007	0.047 ±0.002	0.055 ±0.002	0.045 ±0.0004

Notes:
1. All samples are prepared using Standard Proctor Compactive Effort
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent
3. Mean and one standard deviation is computed for Tests No. CTRC04, CTRC06 CTRC07 and CTRC08 only
4. CR = Compresion ratio, slope of ϵ_v vs. $\log(\sigma_v)$ in virgin zone of compression
   RR = Recompression ratio, average slope of ϵ_v vs. $\log(\sigma_v)$ plot for recompression part of the curve
   SR = Swelling ratio, slope of rebound curve

Table 5:7 Comparison of results from compressibility testing

No. of	Chip Size	Chip Ratio	Dry density	Vertical ϵ_v	Strain (%)	CR for σ_v (psi)			RR σ_v for (psi)		SR for σ_v (psi)
Test	(in)	(%)	(pcf)	σ_v=10psi	σ_v=20psi	2-4	4-10	10-20	4-10	10-20	10-1
8	0.5-2.0	Chip only	40.24 ± 1.314	15.72 ± 1.35	21.59 ± 1.70	0.121 ±0.008	0.169 ±0.011	0.200 ±0.012	0.139 ±0.011	0.178 ±0.008	0.108 ±0.007
1	1.0	37% (chips-sand)	86.10	3.00	4.05	0.023	0.029	0.034	0.019	0.028	0.021
4	0.5-2.0	40% (chips-CB)	71.975 ± 1.377	9.79 ± 0.771	12.57 ± 0.81	0.074 ±0.008	0.096 ±0.007	0.096 ±0.007	0.473 ±0.002	0.055 ±0.002	0.045 ±0.0004

Notes: 1. The results summarized in this table can be found in Tables 5.1 to 5.6

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

3. CR = Compression ratio, slope of ϵ_v vs. log(σ_v) in virgin zone of coompression curve

RR = Recompression ratio, average slope of ϵ_v vs. log(σ_v) for recompression portion of curve

SR = Swelling ratio, slope of rebound curve

corresponding stress levels (see Table 5.1). This may be due to a higher percent of steel in this type of chips, which is reflected in higher density and specific gravity values. A similar trend is observed during rebound. All types of chip samples show some permanent strain at the end of each cycle. This strain is almost 5% at the end of first loading cycle. However, it reduces to about 1% for each subsequent cycle. The sample show a total permanent strain of about 8% at the end of 4th loading cycle.

Figure 5.9 to 5.12 plot data from four load/unload cycles of compression tests on 1-inch chips specimens, prepared using four different levels of compactive energy. The curves display a small effect of compactive effort on the compression of chips, except in the case of samples prepared with no compaction. These loose samples exhibit about 10 to 12% higher strain compared to other samples at corresponding stress levels. The curves from specimens compacted using modified and standard compactive effort almost overlap, while curves from samples compacted with energy equivalent to 50% of a standard Proctor test show comparatively larger compressions. These are about 2 to 3% greater than for the curves from samples prepared with higher compactive efforts (also see Table 5.1). A similar trend is demonstrated in the curves of compression tests on samples of 2-inch chips (see Figures 13 to 16).

Figures 17 to 20 plot the compression curves from tests on 1- and 2-inch size chips, with specimens prepared using three different compactive efforts, i.e., modified, standard, and 50% of standard. The curves from these tests demonstrate remarkable consistency and repeatability of results from compression tests on tire chips. Although the curves show little effect of chip size and compactive effort on the compression behavior of tire chips, the trends are very evident: no effect of compactive effort on compression of chips in case of modified and standard compaction, and slightly higher compression in the case of lesser compactive effort (i.e., 50% of standard compared to standard and modified).

Figures 21 to 23 plot data from compressibility testing of rubber-sand on a vertical strain versus logarithm of vertical stress plot. The curves are presented for three load/unload cycles for different chip/mix ratios, varying from no chips to 100% chips. The curves demonstrate that the compressibility increases with increasing chip ratios. The vertical strain up to 31% chips by weight of mix is very small, i.e., about 3% at 40 psi at the end of third loading cycle. The compressibility significantly increases for chip/mix ratios greater than 37% (see Table 5.2). It has been found during compaction testing of rubber-sand that optimum density is achieved between 38 to 40% chips/mix ratios, the density of mix when all voids are filled with sand. This ratio of chips is also considered appropriate from compression testing results. At this chip/soil ratio, the mix has a density which is about two thirds that of conventional fills and voids between chips are completely filled with sand, thus rendering the mix less liable to large compressions under loads. This chip/mix ratio is suitable for structures where settlement is a matter of concern.

Compression tests were performed on chips-Crosby mixes to determine their compressibility behavior. The variables considered include: 1) chip sizes - chips of four sizes, 0.5, 1.0, 1.5 and 2.0-inch were tested; and 2) chip/mix ratios - varying from 0% chips to 100% chips by weight of mix. The data from compressibility testing of rubber-Crosby are presented graphically in Figures 24 to 29. The curves show that compressibility increases significantly as the chip/mix ratio is increased beyond 15%. The curves in Figures 25 to 27 for 4 different sizes of chips, having 40% chips by weight of mix, and compacted using standard compactive effort show that the size of chips does not significantly effect the compressibility of rubber-Crosby mixes. However, the curves for 2-inch and 0.50-inch chip sizes almost overlap and show greater compressibility compared to mixes containing chip sizes of 1-inch and 1.5-inch (also see Table 5.3). The curves from compressibility testing of rubber-Crosby mix show permanent strains of about 5% at the end of first load/unload cycle. However, only a small amount of permanent strain (about 1%) is observed during subsequent cycles.

Tables 5.1 to 5.3 list the strains computed at two stress levels, i.e., 10 and 20 psi, from tests on tire chips, rubber-sand and rubber-Crosby, respectively. Tables 5.4 to 5.6 summarize the compressibility results in terms of following parameters:

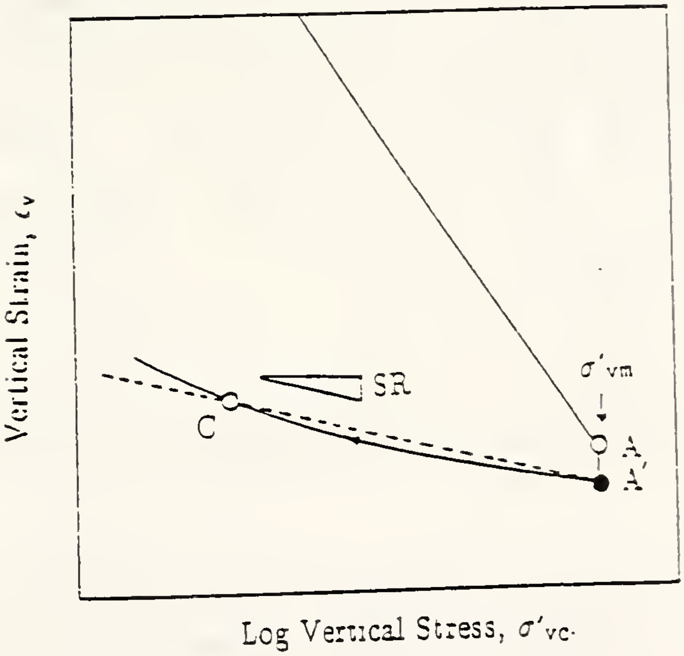
CR = compression ratio or virgin compression ratio, is the slope of ϵ_v versus logarithm of σ_v in virgin zone of the compression curve.

RR = recompression ratio, is average slope of ϵ_v versus logarithm of σ_v plot for recompression portion of curve

SR = swelling ratio, slope of swelling (rebound) curve, this has also been defined in Figure 5.30.

The results from compressibility testing of rubber-soils are compared in Table 5.7. A critical review of the results indicates that rubber-sand mix with 37% chip/mix ratio is a very promising lightweight geomaterial which can be used in highway structures where it is desirable to keep the settlement under load to the minimum.

DEFINITION OF SWELLING RATIO (SR)



$$SR = \frac{(\epsilon_{at}\ A' - \epsilon_{at}\ C)}{\log(\sigma'_{vm}/\sigma'_{at}\ C)}$$

Figure 5.30 Definition of swelling ratio (SR)

5.7 Summary and Conclusions

Compressibility tests were conducted on tire chips, alone and also mixed with soils, to determine the load-deformation behavior of rubber-soils. The testing materials selected for this purpose included: two test soils, Ottawa sand and Crosby till; and tire chips varying in sizes from 0.50 to 2-inch (see Chapter 4 for the engineering properties of these materials). A 12-inch diameter compressibility mold was designed and built for testing large size tire chips. The variables considered included: methods of sample preparation - vibratory and impact compaction; compactive effort - modified, standard, 50% of standard, and no compaction; and chip sizes - varying from 0.50 to 2-inch. The samples were subjected to 3 to 4 load/unload cycles to determine the behavior of rubber-soils under repeated loads.

The data obtained were plotted as vertical strain versus logarithm of vertical stress. Based on a critical analysis of the test results, the following observations are made:

- The load-deformation response of tire chips indicates that three mechanisms are mainly responsible for total compression of tire chip samples: a) compression due to rearrangement/ sliding of chips - a small compression occurs due to this, mainly during first loading cycle and is mostly irrecoverable; b) compression due to bending/flattening of chips - responsible for the major portion of total compression and is mostly recoverable on unloading; and c) compression due to elastic deformation of tire chips - a small compression occurs due to this mechanism and all of it is recoverable. This indicates that compression of rubber chips can be reduced by increasing confining/overburden pressures or filling air voids with material less compressible than tire chips.

- The variation in chip sizes had little effect on load-deformation response for higher compactive efforts, i.e., equivalent to modified and standard Proctor tests. However, a trend of higher vertical strains were observed in the case of 0.5-inch chips, compacted using 50% of standard compactive effort.
- The increase in compactive effort from standard to modified had no effect on the compression curves for various chip sizes. However, samples compacted using 50% of standard Proctor effort yielded vertical strains 2% to 4% higher during the first loading cycle than those compacted with standard or modified effort. The uncompacted samples also produced higher strains during the first loading cycle. However, compactive effort had little effect on the load-deformation response of chips

during subsequent load/unload cycles.

- The curves from rubber-soils with varying chip/mix ratios show that the total compression of samples increases with increasing percent of tire chips, the highest value of compression being for 100% chips. This demonstrates that a blend of rubber-soil provides a mix with lower void ratio, which compresses less than one of pure chips, and will also cause lesser settlement of foundation soil due to reduced weight of fill. About 38% chips by weight of mix is an optimum value for the quantity of chips in a rubber-soil mix, where large settlements are a matter of concern. This chip/soil ratio will yield a compacted dry unit weight of rubber-soil mix which is about two thirds that of soil alone.
- A comparison of vertical strains at different stress levels and compressibility parameters for three materials, i.e., chips, rubber-sand, rubber Crosby, suggests that rubber-sand is a very promising lightweight geomaterial, the use of which should be promoted in fills near bridge abutments, and other highway structures where settlements are to be kept to the minimum.
- A summary of compressibility parameters (CR, RR, and SR) are presented for tire chips, rubber-sand

and rubber-Crosby. These parameters can be used as guides for design and evaluation of embankments incorporating rubber-soils.

CHAPTER 6

SHEAR BEHAVIOR OF RUBBER-SOILS

6.1 Introduction

A testing program has been conducted in a triaxial apparatus with the objective of investigating the shear stress-strain and strength behavior of rubber-soils. The conventional triaxial apparatus could not be used for this purpose due to the large size of the tire chips. A 6-inch diameter triaxial cell was acquired to accommodate tire chips with a maximum size of one inch. The samples were tested dry or at optimum moisture content, to simplify laboratory procedures. Drained conditions were ensured by not saturating the samples and selecting a low shear strain rate.

Currently, a variety of devices are available in the field of geotechnical engineering to measure the stress-strain characteristics as well as limiting conditions in the laboratory under different applied stress systems. Specifically, the direct simple shear, direct shear box, conventional triaxial, prismatic devices (this category of shear devices tests solid prismatic soil specimens and includes some thirteen types of plane strain apparatus, the true triaxial, and directional shear cell), and the torsional shear hollow cylinder are some of the frequently used shear apparatus. Triaxial shear testing equipment was selected for this research for determining the shear behavior of rubber-soils since it represents a commonly used yet versatile type of apparatus for which the stresses on the major and minor principal planes are known, drainage can be controlled, and pore pressures can be conveniently measured, if required. The first results from triaxial tests appear to be those of Staton and Hveem (1934). Since that time, the triaxial test has evolved into the cornerstone test for measuring soil properties. It provides consistent and relatively accurate estimates of shear strength parameters for stability design and analyses with simple testing procedures.

Subsequent sections of this chapter contain: a brief description of the testing apparatus; experimental procedures, including the details of various corrections applied to the measured tests data; an overview of the testing program; presentation of data; and discussion of shear results from testing of tire chips, alone and mixed with soils. A comparison of test results from this research with limited published data is also made. Finally, a summary and salient conclusions are provided at the end of this chapter.

6.2 Description of Testing Apparatus

A 6-inch diameter internal chamber triaxial cell, manufactured on special order by Research Engineering, Inc. Grass Valley, California, was used for measurement of shear strength parameters of rubber-soils. The cell can accommodate sample of 12-inch nominal height. In addition, a 6-inch diameter vacuum split mold and a 6-inch diameter compaction mold were also built for preparation of samples of coarse grained and fine grained soils, respectively. The samples were tested using an MTS Soil Testing System, which can apply a variety of loading conditions in a stress or strain control mode, to simulate field conditions. The loading frame of the MTS Soil Testing System was appropriately modified to accommodate a large size triaxial cell.

6.3 Experimental Procedures

Tire chips of different sizes/gradations and two types of soils, i.e., Ottawa sand and Crosby till, were tested to determine the shear behavior of rubber-soils (see Chapter 4 for the characteristics of tire chips and properties of test soils). The samples of tire chips alone and rubber-sand mixes were tested dry. The samples of rubber-Crosby were tested at optimum moisture content. The samples of tire chips alone were compacted using Proctor type compaction, at variable compactive energy. The samples of sand and rubber-sand mixes were compacted using a vibratory method of compaction. The samples were vibrated at 60 Hz. for 8 minutes under 2 psi of confining pressure (see Figure 6.1). The samples of rubber-Crosby mixes were prepared by the impact type of compaction, using variable compactive energy levels (see Chapter 4 for detailed procedures of sample preparation). Figures 6.2 to 6.7 show rubber-sand samples prepared with variable chip/mix ratios. The rubber-sand samples having chip/mix ratios of about 39% have a homogeneous mix throughout the sample (Figures 6.3 to 6.4). As the chip/mix ratio increases, a portion of the sample at the top shows only chips without sand, which causes a larger compression of the samples.

The prepared sample is enclosed in a double rubber membranes. Weight of the sample, and height, and diameter of the sample are measured and the sample is then assembled in the loading frame of the MTS Soil Testing System (see Figures 6.8 and 6.9). In the case of rubber-sand and rubber chips alone, vacuum is applied at the base of the sample to prevent disturbance of the sample, and also to keep it intact. A seating load is applied to the sample. At this stage, load and LVDT zeros are recorded. The desired confining pressure is applied. The pre-shear load and LVDT readings are taken to compute pre-shear height. The sample is then sheared at a constant rate of strain of 1% per minute. The load versus

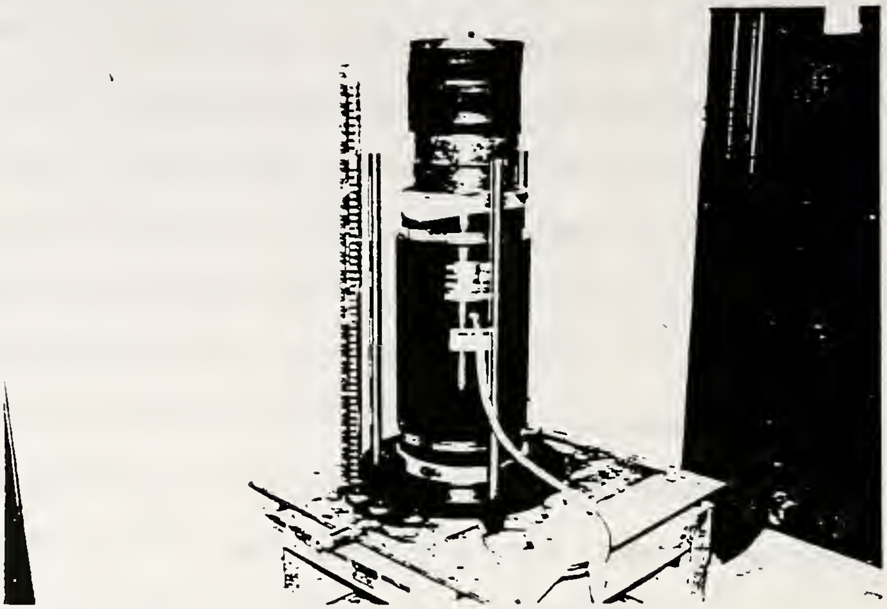


Figure 6.1 Preparation of a rubber-sand sample by vibratory compaction

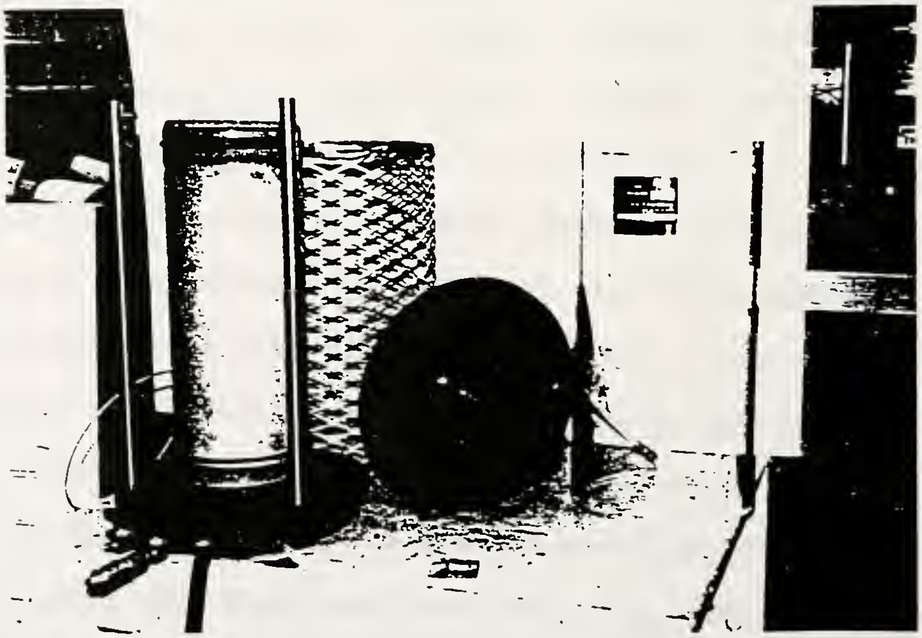


Figure 6.2 A rubber-sand sample enclosed in rubber membrane and under a state of vacuum

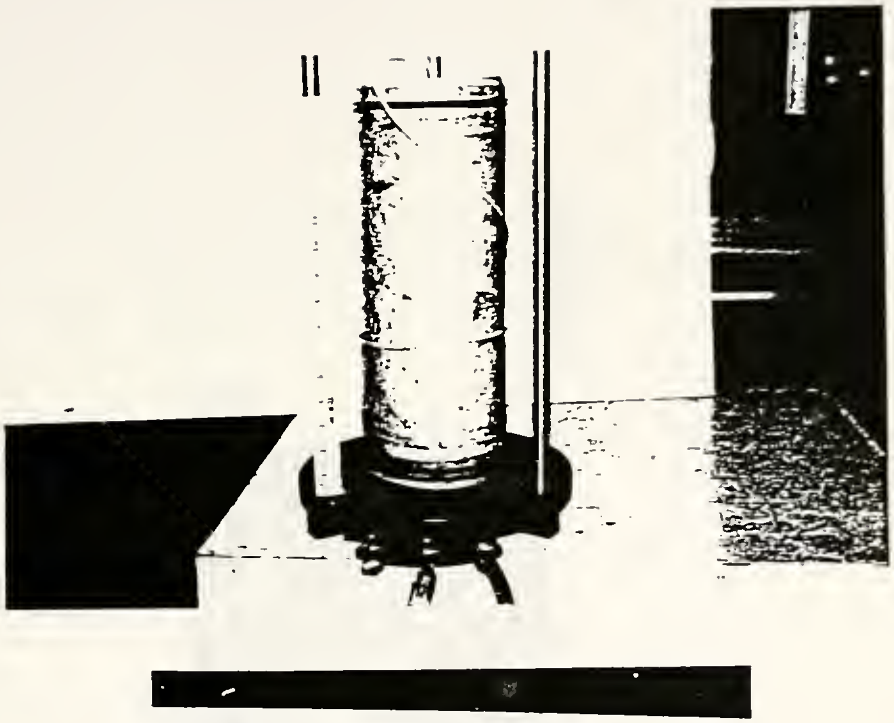


Figure 6.3 A triaxial sample of 1-inch chips/sand mix at optimum ratio (≈ 39% chips)

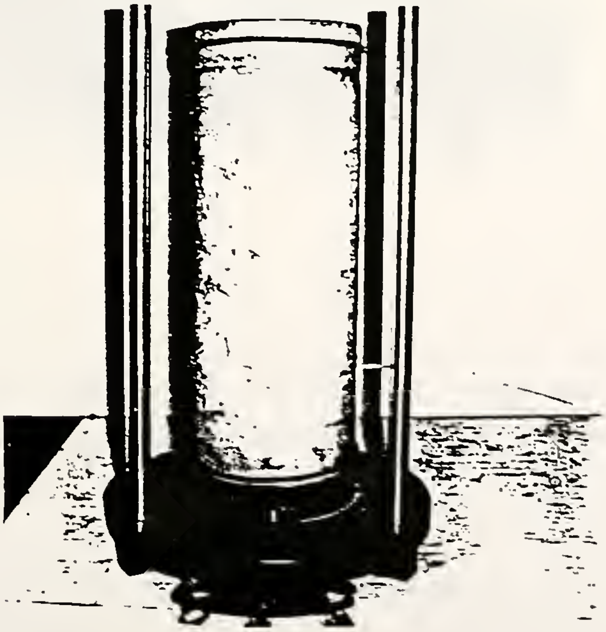


Figure 6.4 A triaxial sample of 0.5-inch chips/mix at optimum ratio (≈ 39% chips)

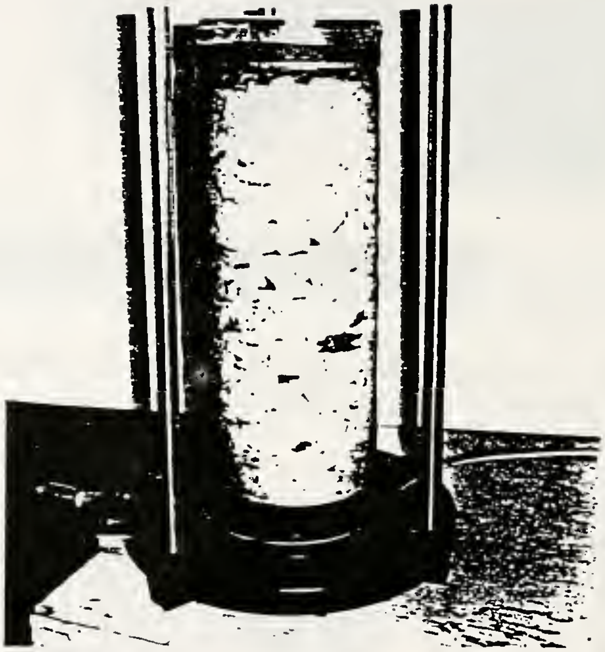


Figure 6.5 A rubber-sand sample at chip/mix ratio of 44%

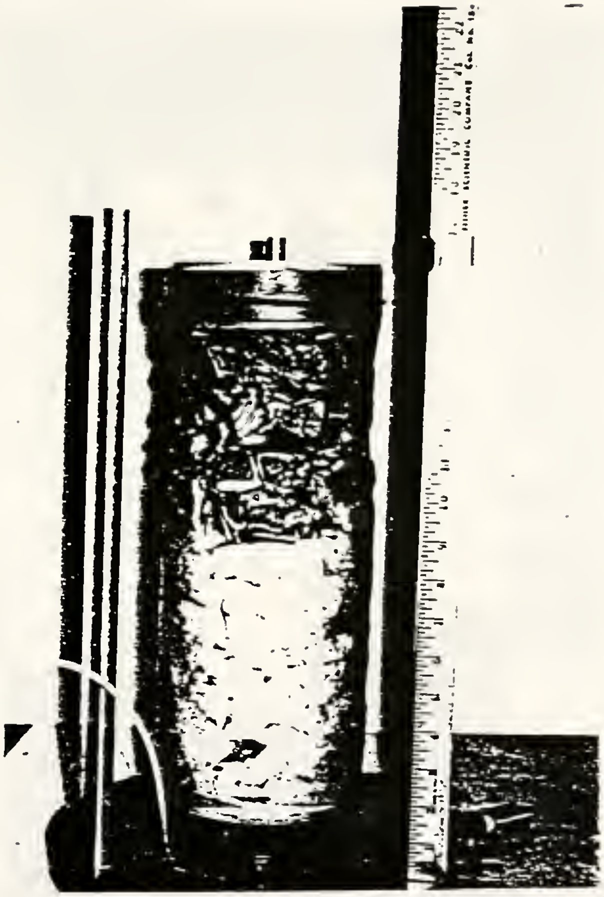


Figure 6.6 A rubber-sand sample at chip/mix ratio of 50%

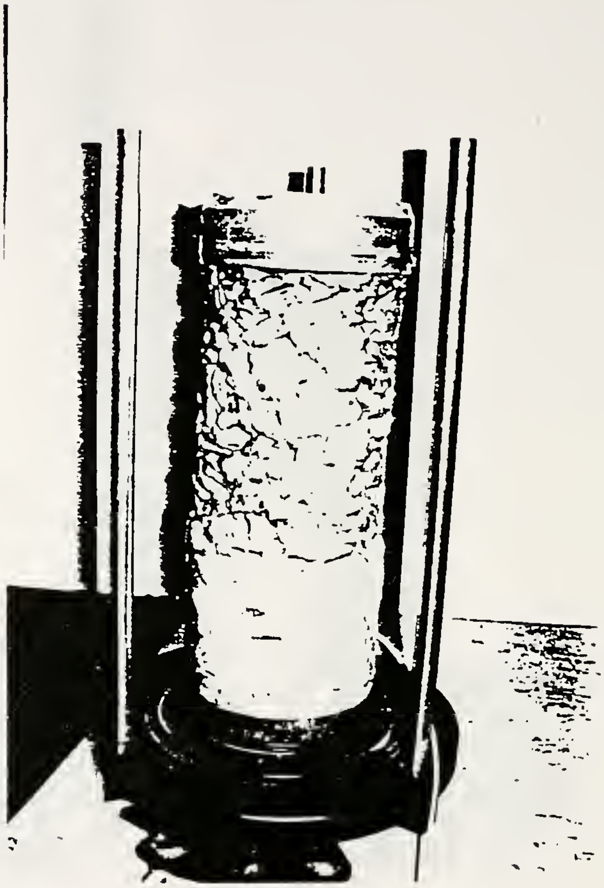


Figure 6.7 A rubber-sand sample at chip/mix ration of 66.5%

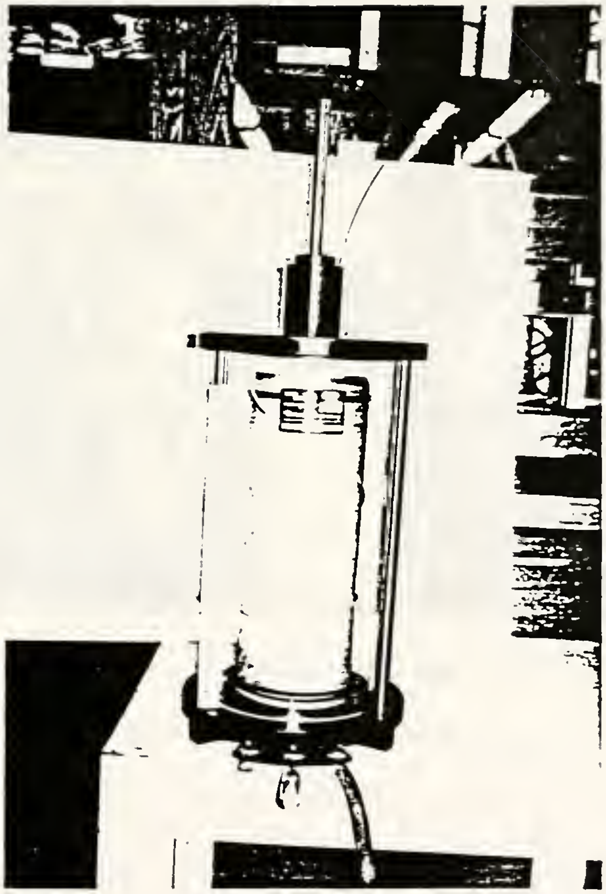


Figure 6.8 A rubber-sand sample set up in 6-inch diameter triaxial cell

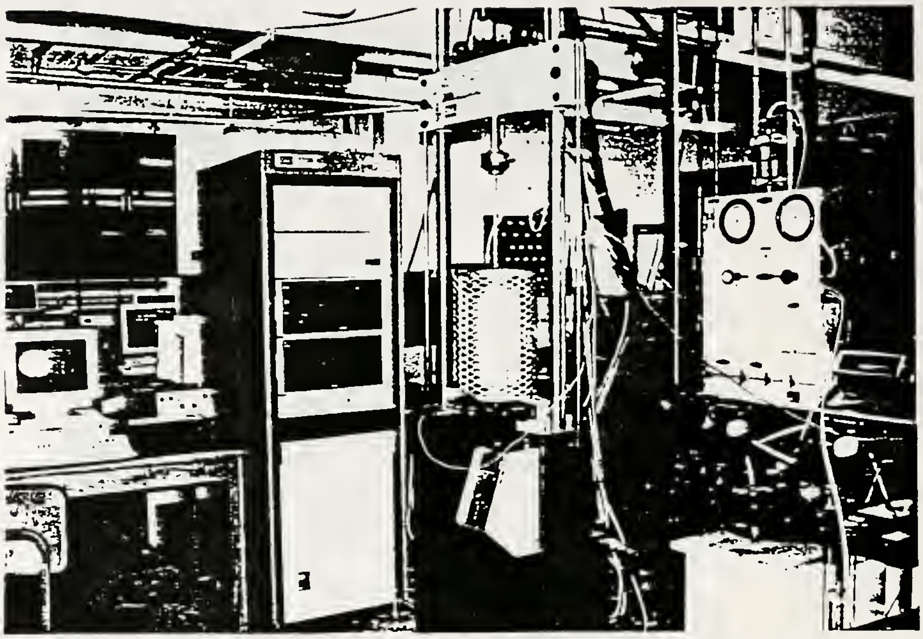


Figure 6.9 A 6-inch diameter triaxial cell mounted in the MTS Soil Testing System for shear testing

deformation is recorded. The data so obtained are corrected, prior to computing deviatoric stresses and the strength parameters (see Appendix B for tabulated data for the individual tests).

Two types of corrections are generally applied to the data obtained from triaxial testing: 1) vertical stress corrections; and 2) area corrections. Corrections commonly made to the vertical stress are to account for piston friction and membrane resistance. The piston friction was considered negligibly small for the large size triaxial cell with 0.75-in. rod type piston, with ball bearings. A membrane correction was determined using the Bishop and Henkel (1962) procedure, which recommends that the correction be applied to the axial stress to account for the restraint imposed on the specimen by the rubber membrane enclosing it. According to Bishop and Henkel (1962), if $(\sigma_1-\sigma_3)_m$ is the measured compression, then the actual compression strength of the sample can be given by:

$$(\sigma_1-\sigma_3) = (\sigma_1-\sigma_3)_m - \frac{\pi D M \epsilon}{a} \qquad (6.1)$$

Where,

a = corrected area of the sample at axial strain, ϵ

D = initial diameter of the sample

M = compression modulus of the rubber membrane, per unit width

The corrected stress, σ_r, to the measured compression strength, due to the effect of the rubber membrane, is therefore:

$$\sigma_r = \frac{\pi D M \epsilon}{a} = \frac{\pi D M \epsilon (1-\epsilon)}{a_0} \qquad (6.2)$$

Where a_0 is the initial cross-sectional area of the specimen.

The compression modulus, M, of the rubber membranes used in this research was measured in the laboratory according to the procedures described by Bishop and Henkel (1962). The method requires measurement of load-deformation response of 1-inch wide rubber membrane strip. The modulus is computed using equation:

$$M = \frac{load per inch}{strain} \qquad (6.3)$$

M for the rubber membranes used for this research was found to be 1.03 psi. The membrane correction was computed using Equation 6.2. The value of corrected σ_r was obtained as

0.143 psi at 30% strain, which was considered very small and was neglected.

Area correction represents the largest source of errors in any test with direct measurements (Germaine, 1985). Several types of corrections are suggested to account for the changes in the cross-sectional area of the sample due to vertical deformation during shearing. The cylindrical correction is most common. However, below 10% strain all give acceptable results (Germaine, 1985). The particular choice is based on the final observed geometry. In the case of this research, the cylindrical correction was considered appropriate and was applied for computing the corrected area, as follows:

$$A_c = \frac{A_i}{1 - \frac{d_p}{H_0}} \qquad (6.4)$$

Where,

A_c = corrected area

A_i = initial area

d_p = permanent vertical displacement

H_0 = initial height of the sample.

The deviatoric stress is computed by dividing the measured load by the corrected area.

6.4 Laboratory Testing Program

The testing program was carefully planned to achieve the research objectives set forth in Chapter 1. A total of 58 drained triaxial compression tests were performed on rubber-soils samples to determine their stress-strain and strength behavior. The variables considered included: type of soils, Ottawa sand and Crosby till representing the family of coarse and fine grained soils, respectively; methods of compaction, vibratory and Proctor type compaction; levels of compactive energy, three compactive effort were considered; size of chips, 0.5 and 1-inch; chip/mix ratios, the ratios were varied from 0 to 100%; and confining pressures, varied from 4.5 to 30 psi. Tables 6.1 to 6.3 summarize the details of the testing program.

6.5 Presentation of Shear Results

The results of the shear tests are presented graphically and also summarized in tables. Figures 6.10 to 6.12 are the plots of deviatoric stress versus axial strain for samples of 1-inch chips compacted using modified, standard, and 50% of standard Proctor energy, respectively. Figure 6.13 plots data from 0.5-inch size chips, compacted using standard Proctor energy. Figures 6.14 to 6.16 present stress-strain plots for variable compactive effort and three levels of confining pressures, i.e., 4.5 to 4.6 psi, 14.4 to 14.5 psi, and 28.7 to 28.9 psi. Figures 6.17 to 6.30 and Figures 6.31

Table 6.1 Testing program and deviatoric stresses at different strain levels for tire chips

Test No.	Size of Chips (inch)	Compaction	Dry Density (pcf)	Confining Pressure (psi)	Deviatoric Stress at Strain Levels (psi)			
					5%	10%	15%	20%
TPC01	1.00	Modified	42.33	4.64	7.21	12.61	18.47	24.32
TPC02	1.00	Modified	42.85	14.36	9.68	18.02	27.93	38.29
TPC03	1.00	Modified	43.73	28.86	14.41	28.38	43.06	59.01
TPC04	1.00	Standard	40.39	0.00	4.62	8.67	12.72	16.76
TPC05	1.00	Standard	41.13	4.64	6.93	12.14	17.34	23.12
TPC06	1.00	Standard	40.68	16.53	9.83	18.21	27.17	38.15
TPC07	1.00	Standard	41.57	28.71	15.03	28.32	42.77	58.96
TPC08	1.00	Standard	40.45	44.52	18.50	33.53	52.02	70.52
TPC09	1.00	50% Standard	40.10	4.5	6.76	11.71	16.67	21.62
TPC10	1.00	50% Standard	40.35	14.36	10.98	17.12	25.68	34.68
TPC11	1.00	50% Standard	40.26	28.86	16.76	25.23	37.84	52.25
TPC12	0.50	Standard	39.99	5.22	5.76	10.43	15.11	20.00
TPC13	0.50	Standard	39.05	12.76	7.91	14.39	21.58	29.50
TPC14	0.50	Standard	39.00	28.86	12.23	21.94	33.09	45.68

Notes:
1. Modified = Modified Proctor Energy = 56,250 ft-lb/ft^3
2. Standard = Standard Proctor Energy = 12,375 ft-lb/ft^3
3. 50% Standard = 50% Standard Proctor Energy = 6,188 ft-lb/ft^3

Table 6.2 Testing program and deviatoric stresses at different strain levels for rubber-sand

Test No.	Size of Chips (inch)	% Chips	Dry Density (pcf)	Confining Pressure (psi)	Deviatoric Stress at Strain Levels (psi)			
					5%	10%	15%	20%
TRS01	No Chip	0	115.68	4.50	4.5	17.74	-	-
TRS02	No Chip	0	115.77	14.36	14.36	52.15	-	-
TRS03	No Chip	0	115.30	28.86	28.86	112.36	-	-
TRS04	1.00	16.5	101.55	4.64	4.64	23.66	20.00	-
TRS05	1.00	16.5	103.02	14.50	14.5	56.45	55.91	-
TRS06	1.00	16.5	103.18	28.86	28.86	96.77	101.08	-
TRS07	1.00	29.16	96.17	4.50	4.5	28.49	27.96	-
TRS08	1.00	19.16	94.20	14.50	14.5	54.30	64.52	-
TRS09	1.00	29.16	94.22	28.86	28.86	76.34	104.84	-
TRS10	1.00	40.00	84.61	4.64	4.64	22.50	31.25	27.96
TRS11	1.00	40.00	84.61	14.36	14.36	36.88	60.00	66.13
TRS12	1.00	40.00	85.02	28.86	28.86	54.38	88.75	110.75
TRS13	1.00	50.00	72.28	4.64	4.64	6.31	22.52	27.93
TRS14	1.00	50.00	73.08	14.36	14.36	9.01	39.64	53.60
TRS15	1.00	50.00	72.73	28.71	28.71	31.08	59.95	87.39
TRS16	1.00	66.54	55.08	4.50	4.5	7.21	9.01	20.72
TRS17	1.00	66.54	54.41	14.36	14.36	11.26	22.07	33.78
TRS18	1.00	66.54	54.68	28.71	28.71	17.12	33.33	50.00
TRS19	0.50	37.85	87.11	4.64	4.64	23.38	34.53	40.00
TRS20	0.50	37.85	86.32	14.50	14.5	35.25	57.55	69.78
TRS21	0.50	37.85	87.11	28.71	28.71	53.96	90.65	119.42
TRS22	1.00	38.78	88.28	4.64	4.64	28.75	34.38	35.63
TRS23	1.00	39.32	89.25	14.36	14.36	46.88	65.00	68.75
TRS24	1.00	39.37	88.94	28.71	28.71	65.31	98.13	113.44

Notes
1. All samples are prepared by using vibratory compaction
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent

Table 6.3 Testing program and deviatoric stresses at different strain levels for rubber-Crosby till

Test No.	Size of Chips (in.)	% Chips	Compaction	Dry Density (pcf)	Confining Pressure (psi)	Deviatoric Stress at Strain Levels (psi)			
						5%	10%	15%	20%
TRC01	No Chip	0	Standard	119.21	4.50	29.57	45.16	48.39	48.39
TRC02	No Chip	0	Standard	119.67	14.50	41.40	64.52	70.97	71.51
TRC03	No Chip	0	Standard	119.02	28.71	65.59	91.94	98.92	100.00
TRC04	1.00	16.27	Standard	100.94	4.64	29.38	45.00	46.88	43.75
TRC05	1.00	16.27	Standard	101.05	14.36	43.75	65.63	76.25	81.25
TRC06	1.00	16.27	Standard	101.00	28.71	60.00	110.63	110.63	123.75
TRC07	1.00	30.18	Standard	89.17	44.52	21.51	37.10	44.62	47.35
TRC08	1.00	30.18	Standard	88.17	14.36	29.03	49.46	66.13	77.42
TRC09	1.00	30.18	Standard	88.23	28.86	38.71	66.13	88.71	106.45
TRC10	1.00	40.05	Standard	81.41	4.64	17.20	29.57	39.25	45.70
TRC11	1.00	40.05	Standard	81.01	14.36	21.51	39.25	53.38	58.28
TRC12	1.00	40.05	Standard	81.13	28.71	30.65	56.45	79.03	99.46
TRC13	1.00	48.49	Standard	71.56	4.64	14.52	25.27	35.48	43.01
TRC14	1.00	48.49	Standard	70.88	14.36	20.00	36.02	51.08	64.52
TRC15	1.00	48.49	Standard	71.74	28.86	26.88	51.08	74.19	95.70
TRC16	0.50	39.80	Standard	75.98	4.64	15.11	25.90	35.25	-
TRC17	0.50	39.80	Standard	76.56	14.36	17.99	33.09	48.48	-
TRC18	0.50	39.80	Standard	76.79	28.86	21.58	39.57	57.55	-
TRC19	0.50	39.64	50% Standard	73.70	14.36	18.13	33.13	48.13	-
TRC20	0.50	39.79	Modified	78.84	14.36	25.63	48.13	70.63	-

Notes:
1. Modified = Modified Proctor Energy = 56,250 ft-lb/ft^3
2. Standard = Standard Proctor Energy = 12,375 ft-lb/ft^3
3. 50% Standard = 50% of Standard Proctor Energy = 6,188 ft-lb/ft^3

to 6.43 present the synthesized plots of deviatoric stress versus axial strain for variable confining pressures, variable compactive efforts, and for variable chip sizes for rubber-sand and rubber-Crosby mixes, respectively.

Tables 6.1 to 6.3 present the testing program and a summary of deviatoric stresses at four different strain levels for tire chips, rubber-sand, and rubber-Crosby till, respectively. Tables 6.4 to 6.6 contain the basic information about the tests and summarize the strength parameters for tire chips, rubber-sand, and rubber-Crosby till, respectively. Table 6.7 compares the strength parameters published in the literature with the results from the author's laboratory testing of rubber-soils.

6.6 Discussion

6.6.1 Shear Behavior of Tire Chips

Figures 6.10 to 6.12 present the data from triaxial testing of 1-inch size tire chips at confining pressures ranging from 4.5 to 28.9 psi, with samples prepared using compactive effort equivalent to modified, standard, and 50% of standard Proctor energy. It is observed that the samples strain harden with increasing strains and the increase in deviatoric stress is almost linear with increase in axial straining. The deviatoric stress at different strain levels increases with increasing confining pressures. The samples

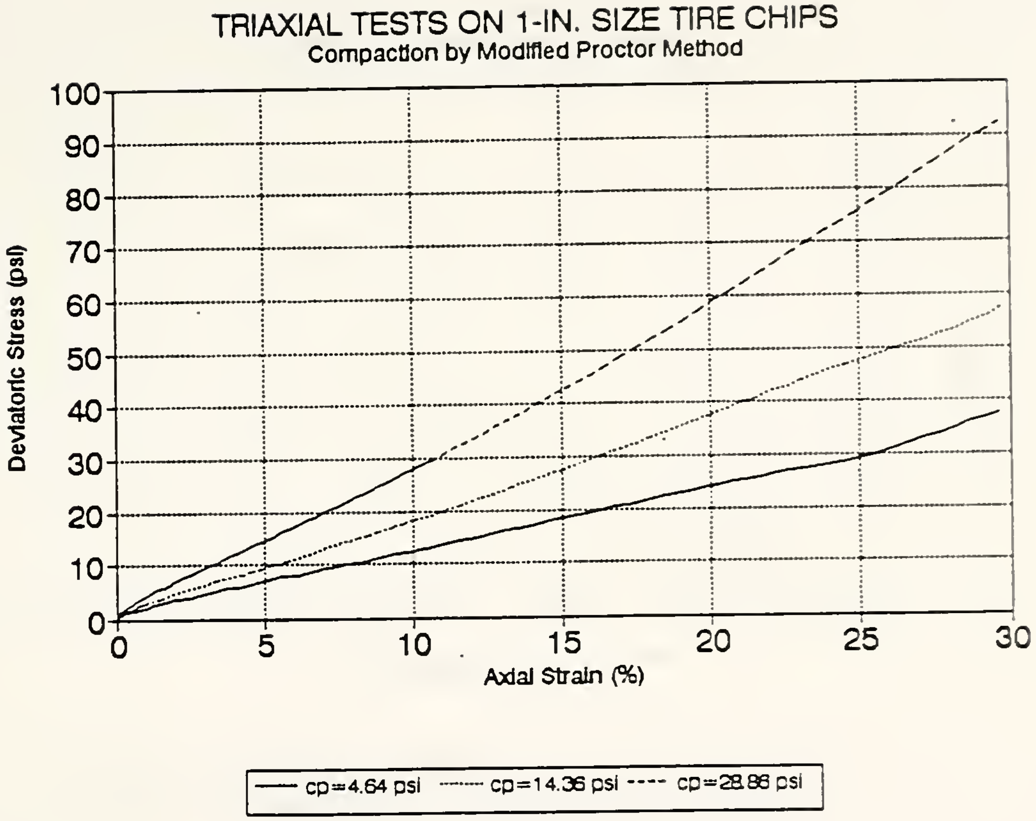


Figure 6.10 Triaxial compression testing of 1-inch size tire chips - compaction by modified Proctor method

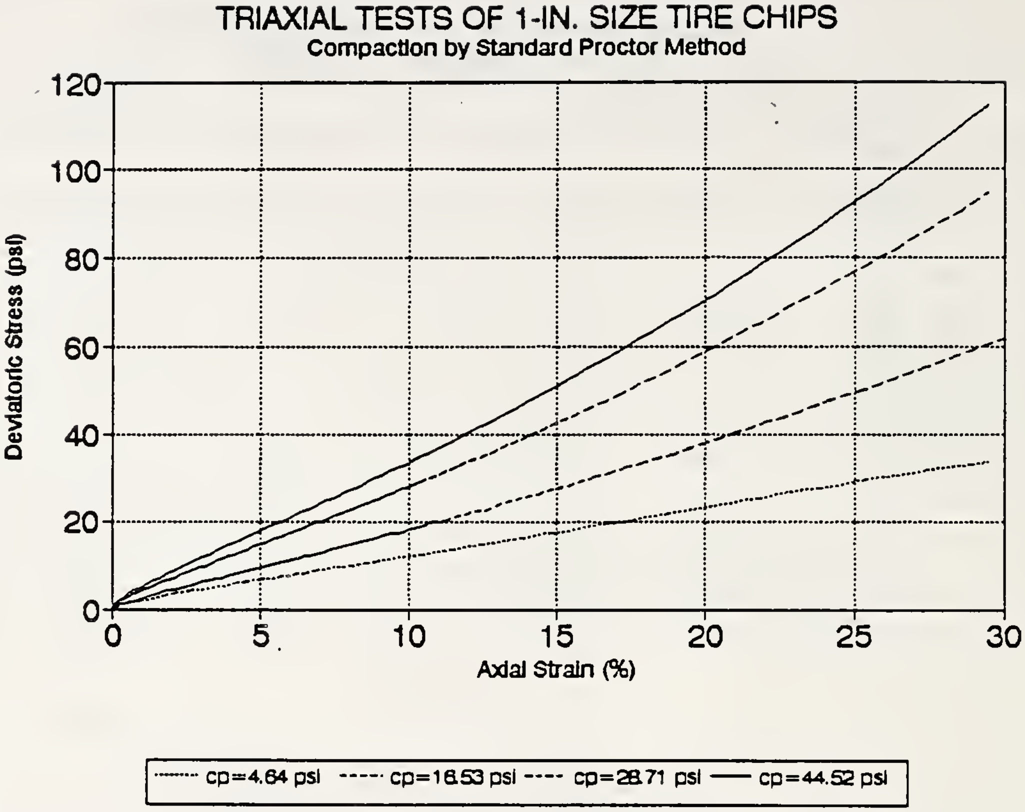


Figure 6.11 Triaxial compression testing of 1-inch size tire chips - compaction by standard Proctor method

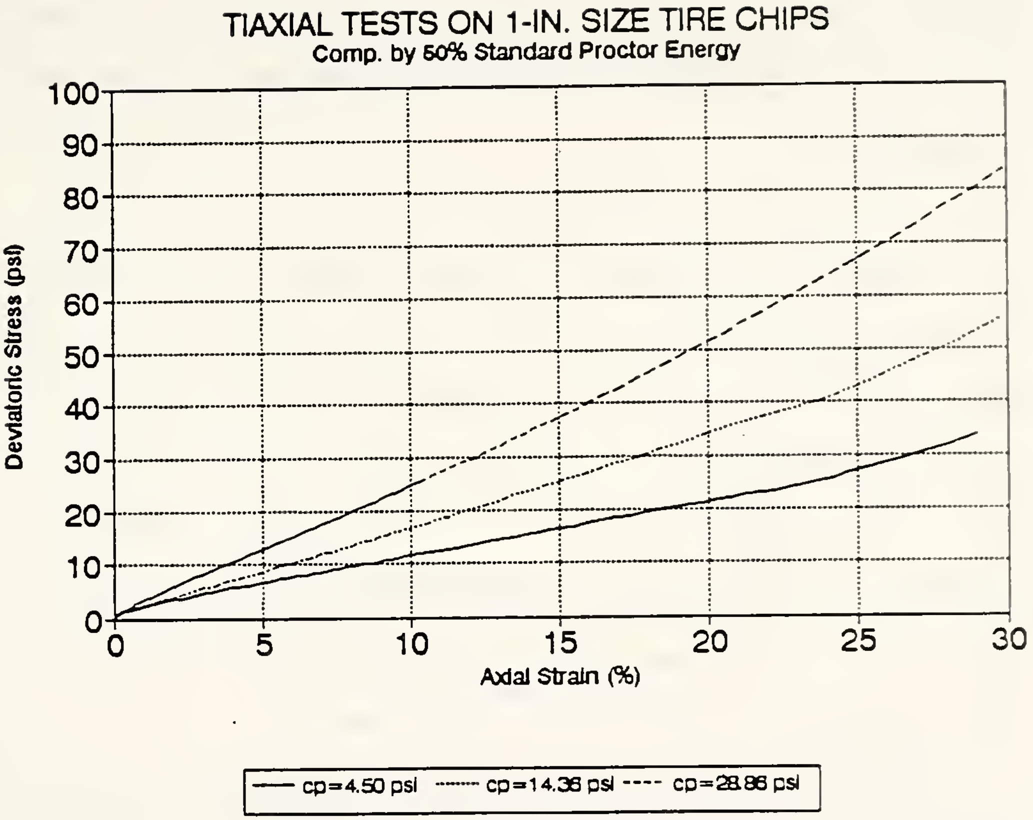


Figure 6.12 Triaxial compression testing of 1-inch size tire chips - compaction by impact energy equivalent to 50% of standard Proctor method

at low confining pressure fail by symmetrical bulging and not on a single shear plane. At high confining pressures (≈28 psi), the samples compress vertically and there is very little or no lateral bulging. The samples continue to become stiffer even beyond 30% strain, when apparatus capacity for measuring the load-deformation response of the samples is reached.

Figures 6.13 plot the shear data on deviatoric stress versus axial strain plot for 0.5-inch size chips sheared at three different confining pressures ranging from 4.5 to 28.9 psi. The shape of curves and the behavior of chips during shear is similar to that described for 1-inch size chips. However, the deviatoric stresses measured at different strain levels for 0.5-inch chips are lower than 1-inch size chips at corresponding strain levels (see Table 6.1). Figures 6.14 to 6.16 plot the data from samples compacted with variable compactive effort for three levels of confining pressures, i.e., 4.5, 14.5, 28.8 psi, respectively. The curves demonstrate that the compactive effort has a small effect on the shear behavior of chips at low confining pressures, but very little effect at higher confining pressures. In fact the stress-strain curves from samples compacted with modified and standard Proctor energy almost overlap.

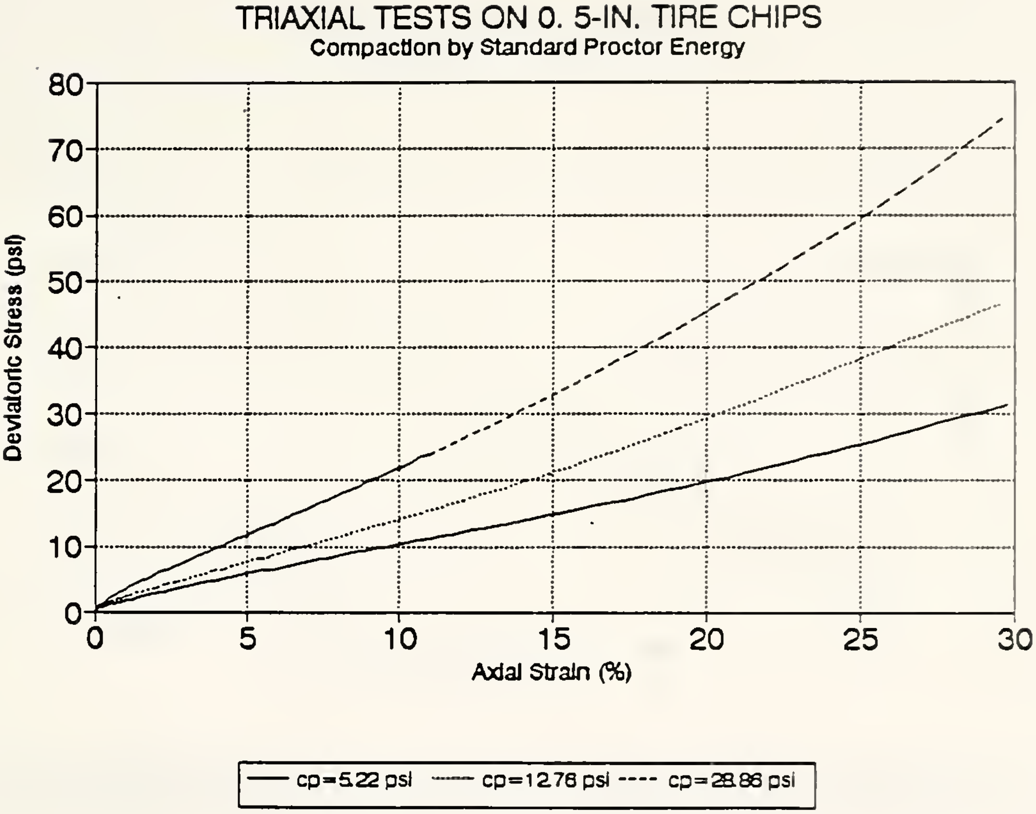


Figure 6.13 Triaxial testing of 0.5-inch size tire chips - compaction by standard Proctor energy

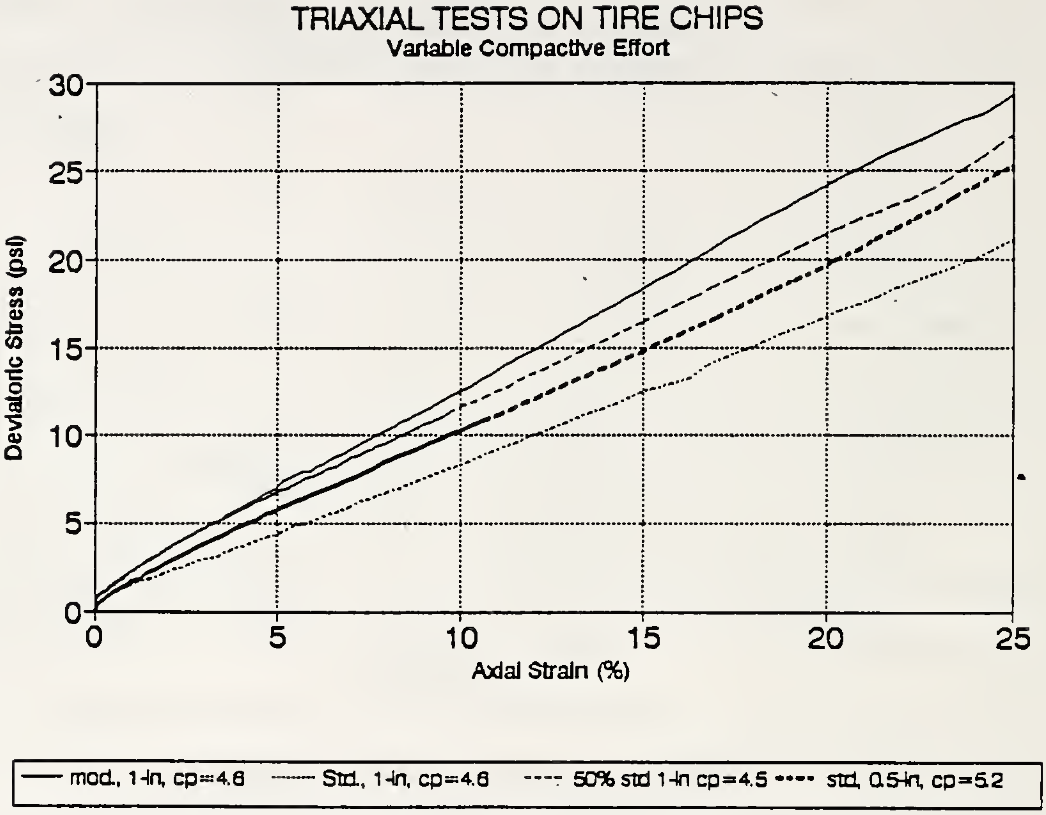


Figure 6.14 Triaxial testing of tire chips at variable compactive efforts and size of chips, at low confining pressure (≈4.6 psi)

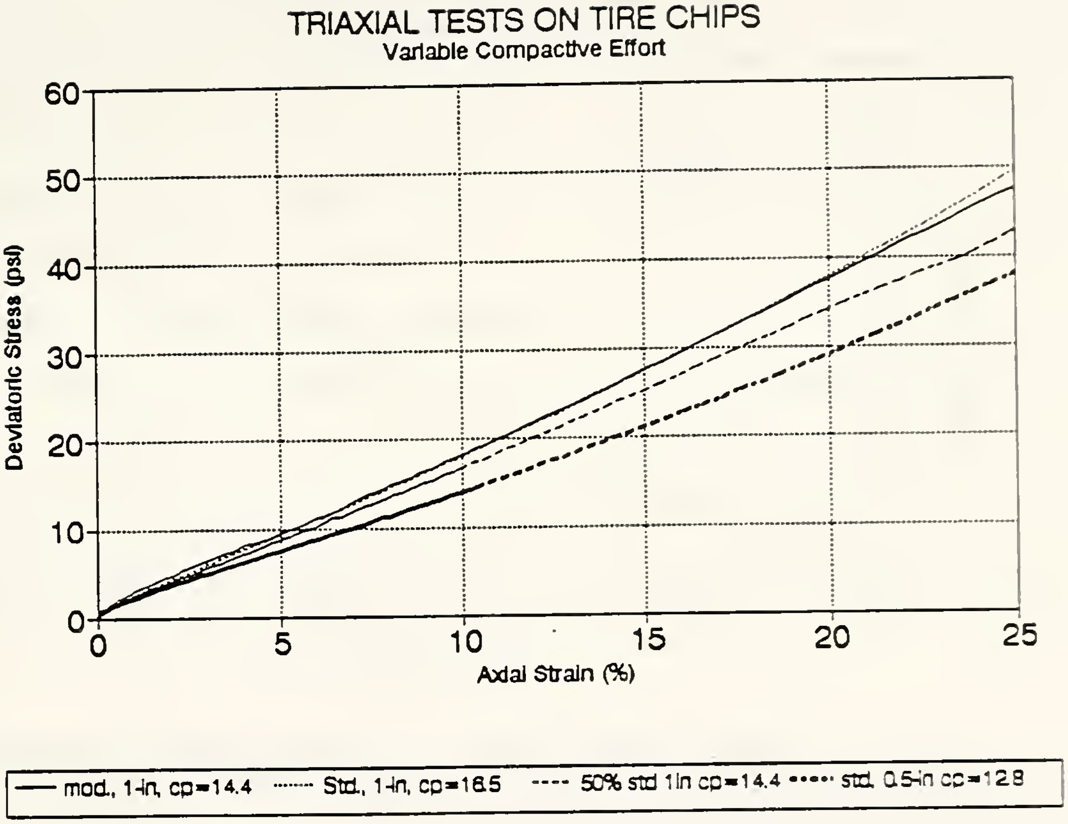


Figure 6.15 Triaxial testing of tire chips at variable compactive efforts and size of chips, at medium confining pressure (≈14.5 psi)

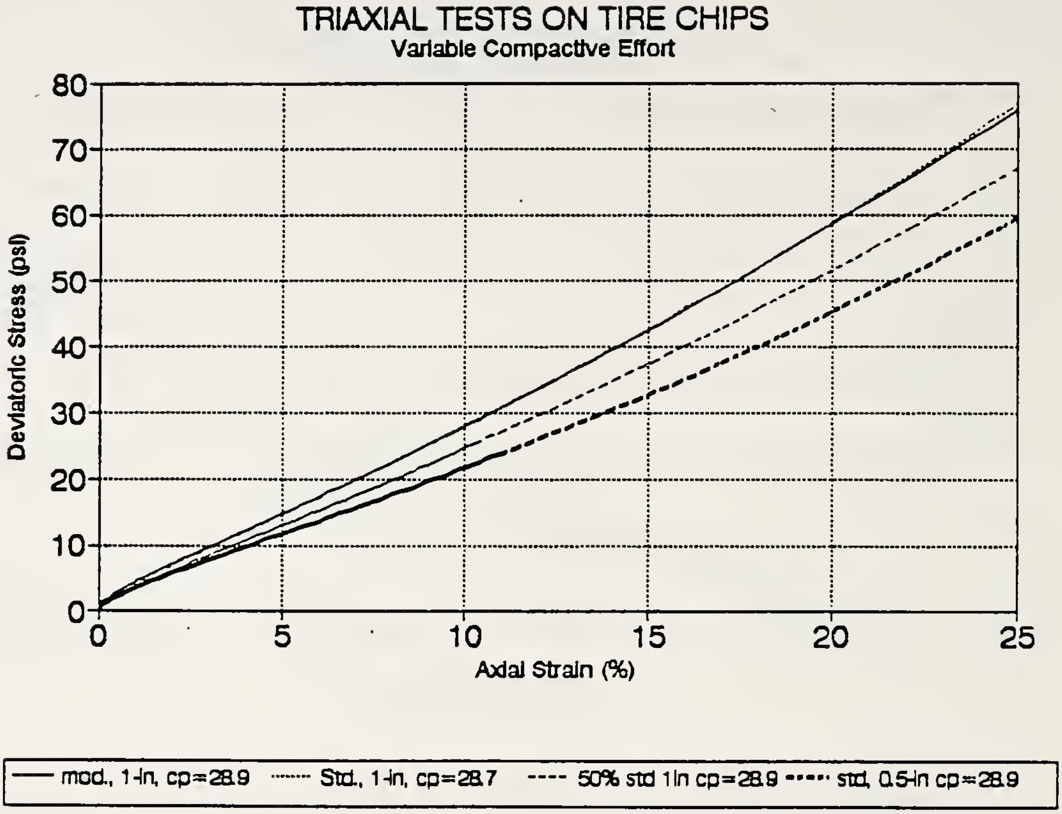


Figure 6.16 Triaxial testing of tire chips at variable compactive efforts and size of chips, at high confining pressure (≈28.5 psi)

6.6.2 Shear Behavior of Rubber-Sand in Triaxial Testing

Figures 6.17 through 6.22 plot the data from triaxial compression tests on rubber-sand with chip/mix ratios varying from 0 to 67% for three levels of confining pressures, i.e., 4.5, 14.5, and 28.9 psi. The sand samples fail along a distinct shear plane (see Figure 6.23); the tire chip samples either fail with symmetrical bulging (at low confining pressures; see Figure 6.24) or compress vertically with increased strain hardening, with little lateral deformation (Figure 6.25). The plots show that as the chip/mix ratios increase, the stress-strain behavior changes from that for sand alone to tire chips alone. The rubber-sand mixes with 0.5-inch chips size yield lower values of deviatoric stress than rubber-sand mixes with 1-inch chips, at corresponding strain levels (see Figures 6.26 to 6.27 and Table 6.2).

Figures 6.28 to 6.30 plot the triaxial compression data from 18 tests from rubber-sand samples with variable chip/mix ratios at three levels of confining pressures. The stress-strain curves demonstrate that increases in chip/mix ratios increase the strain at failure and yield higher maximum deviatoric stresses up to chip/mix ratio of about 40% for low and medium levels of confining pressures (i.e., 4.5 and 14.5 psi). The deviatoric stress drops significantly if chip/mix ratio is increased beyond 40%. At higher confining pressures, the increase in deviatoric stress for rubber-soils

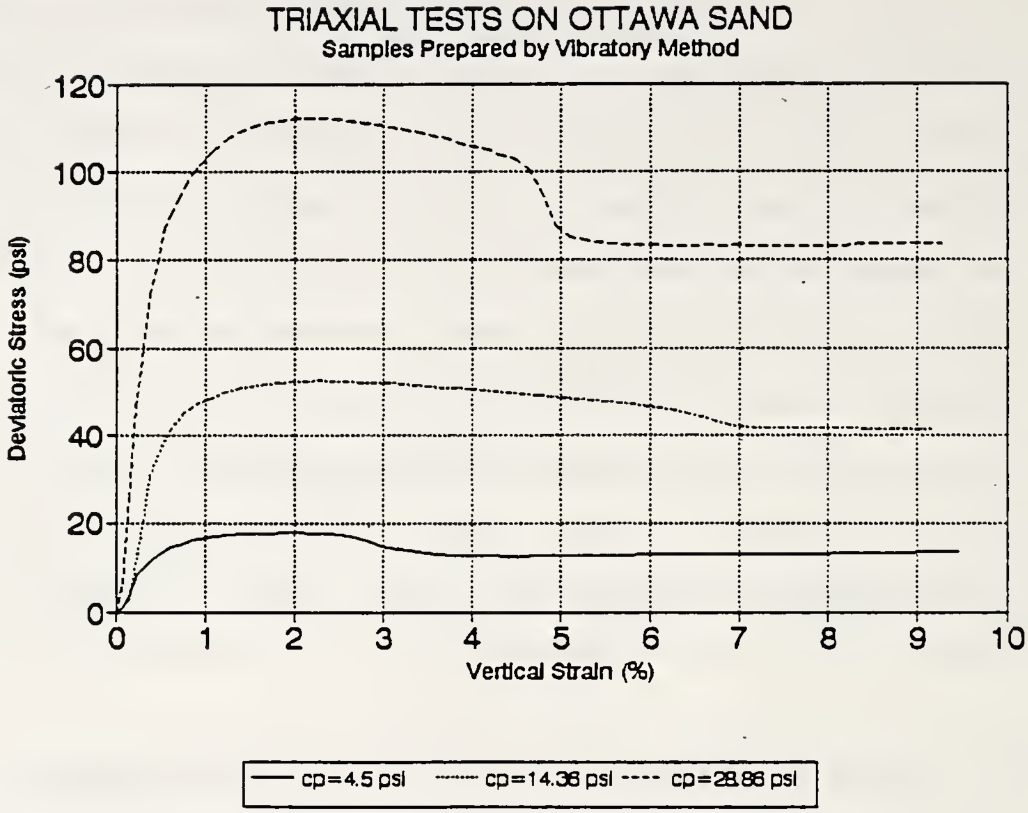


Figure 6.17 Triaxial compression testing of Ottawa sand

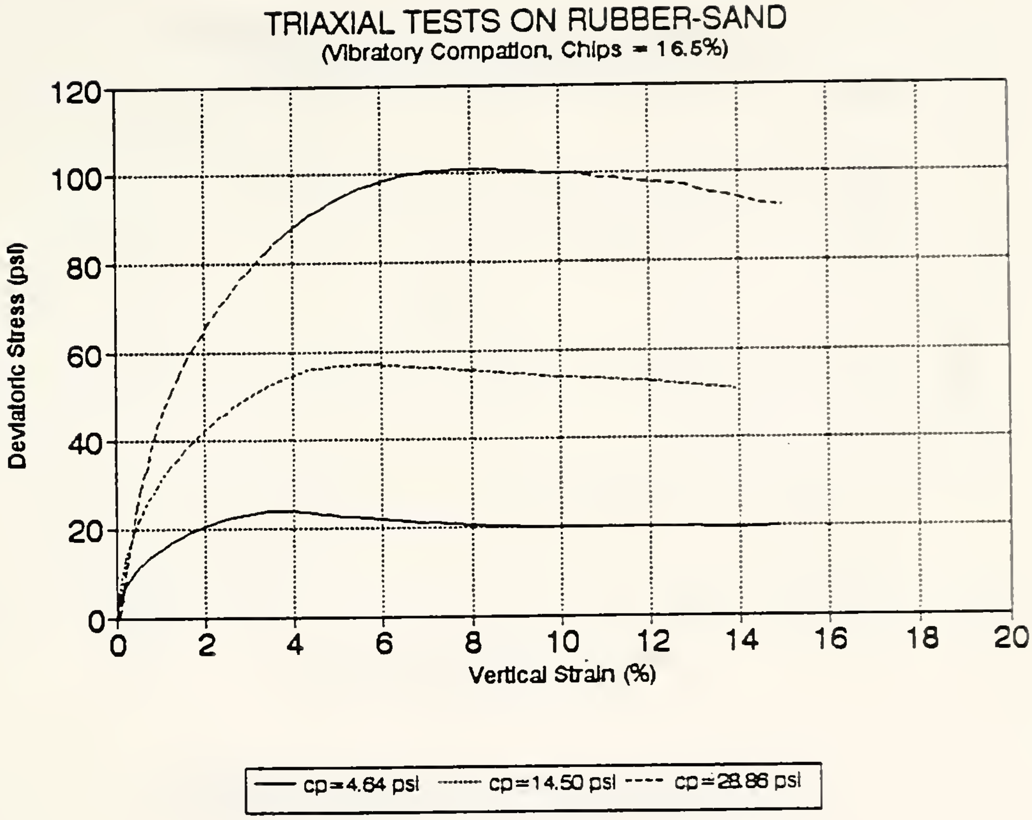


Figure 6.18 Triaxial compression tests on rubber-sand, chips/mix ratio equal to 16.5%

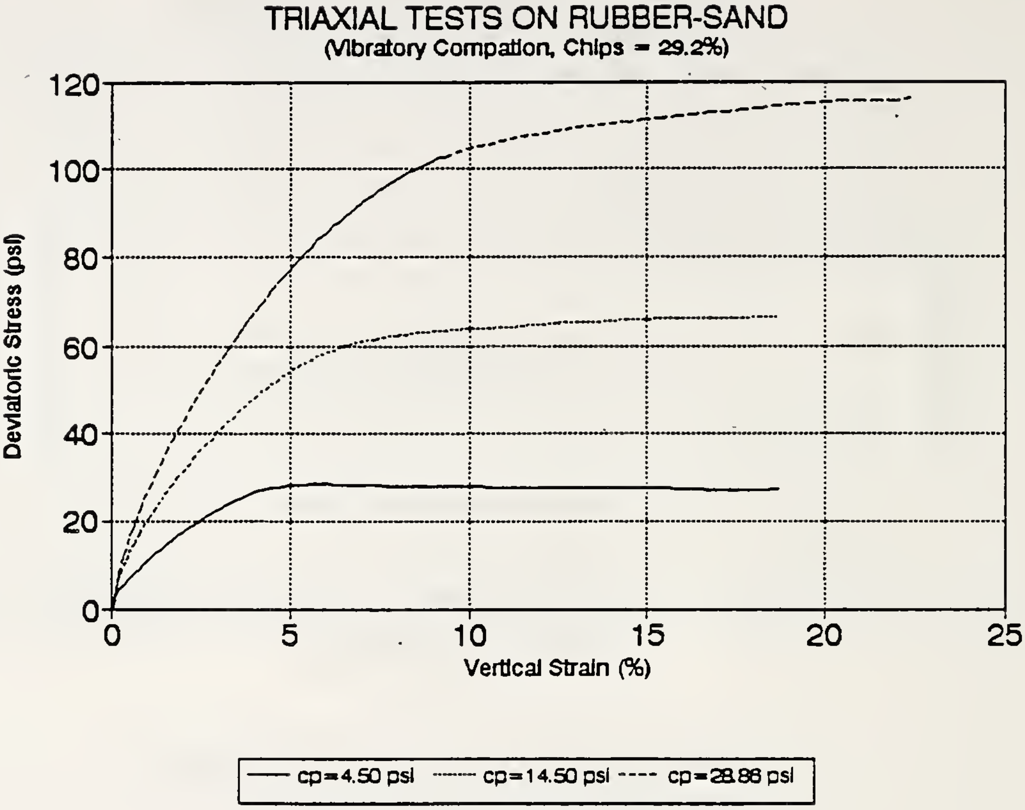


Figure 6.19 Triaxial compression tests on rubber-sand, chips/mix ratio equal to 29.2%

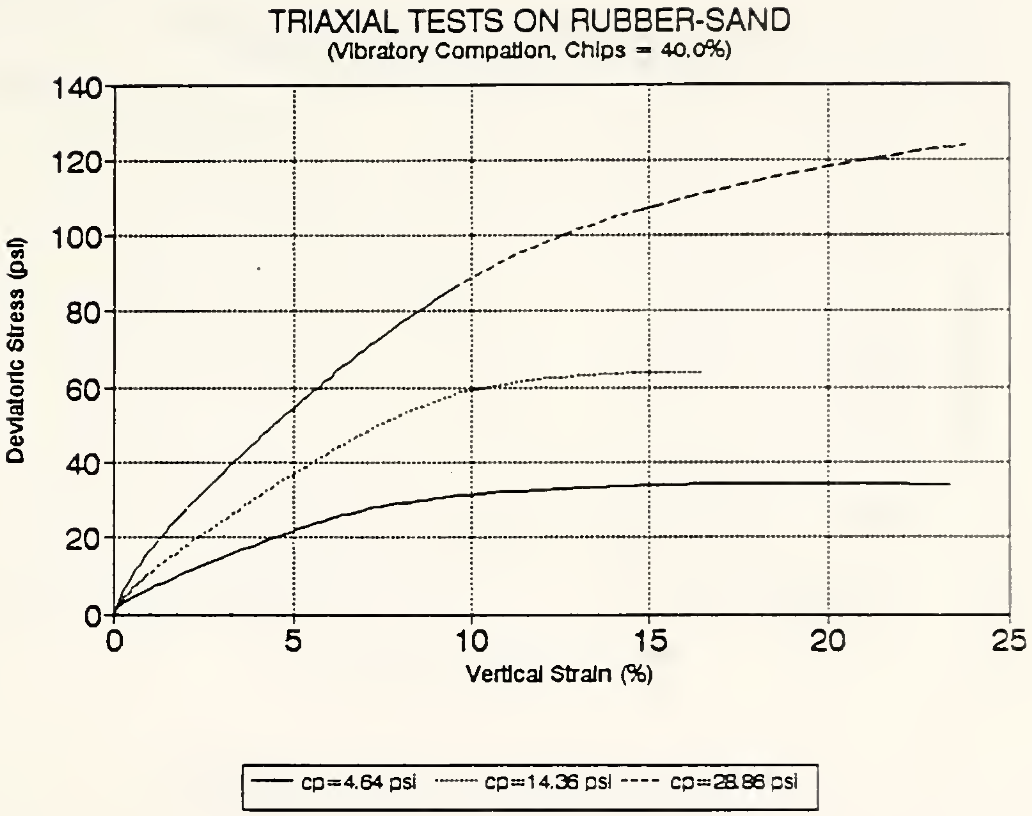


Figure 6.20 Triaxial compression tests on rubber-sand, chips/mix ratio equal to 40%

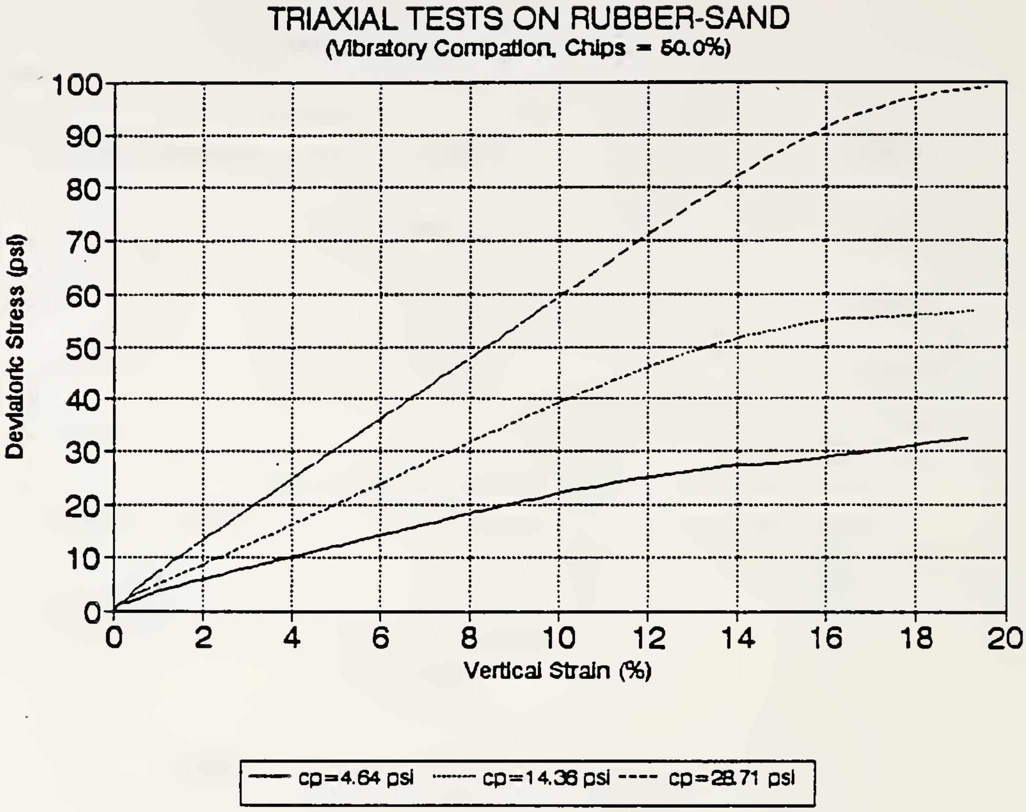


Figure 6.21 Triaxial compression tests on rubber-sand, chips/mix ratio equal to 50%

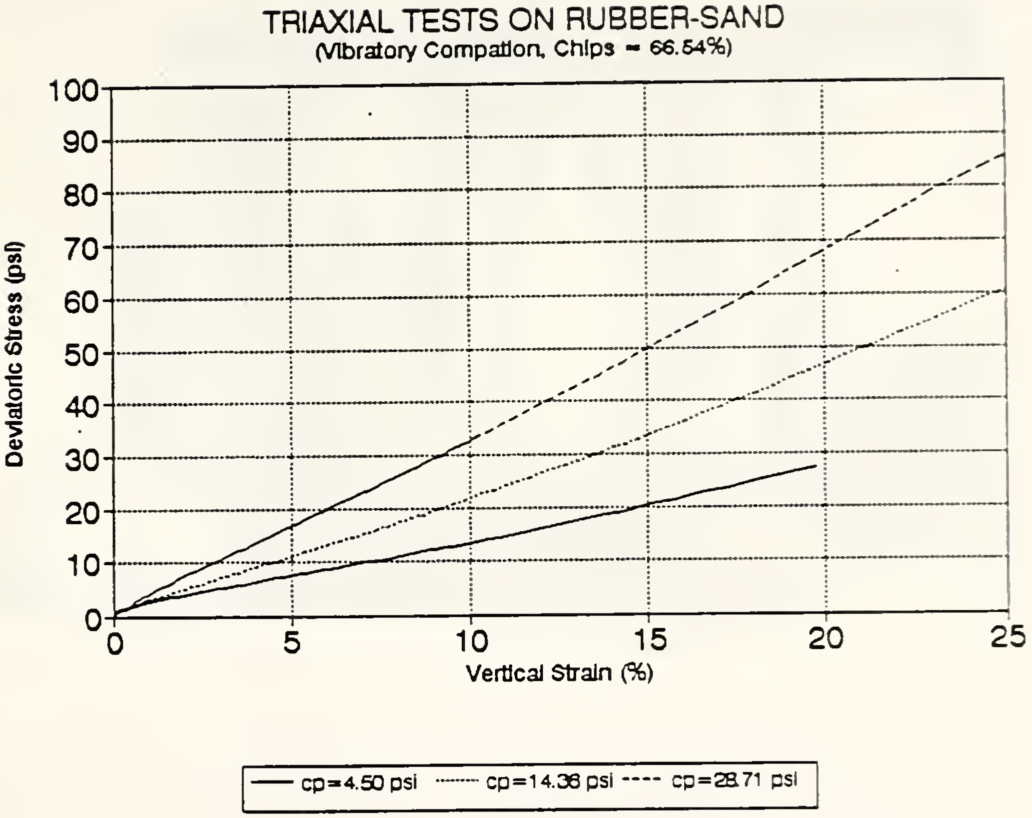


Figure 6.22 Triaxial compression tests on rubber-sand, chips/mix ratio equal to 66.5%

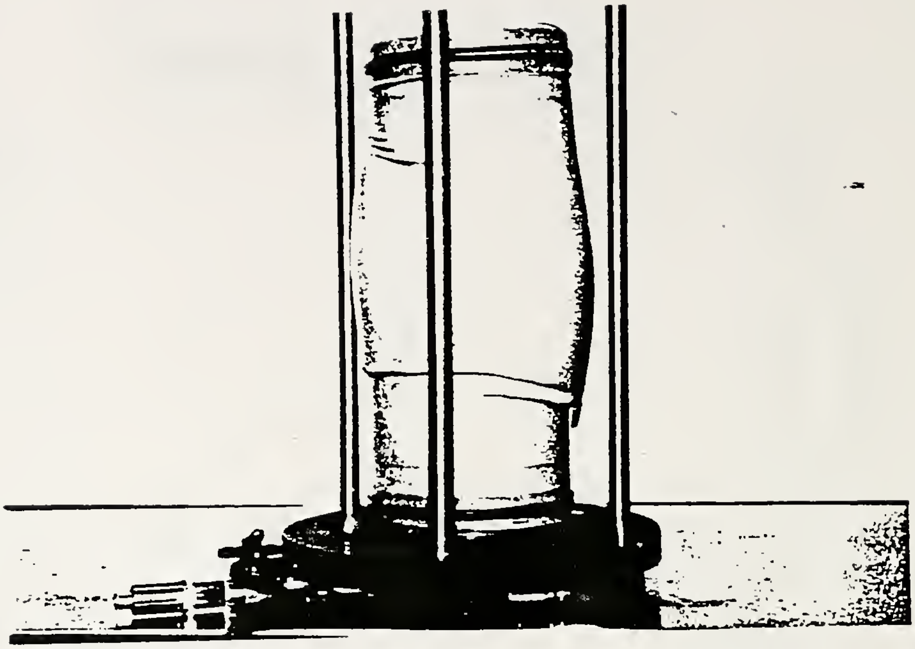


Figure 6.23 An Ottawa sand sample after shearing - an example of failure at single shear plane

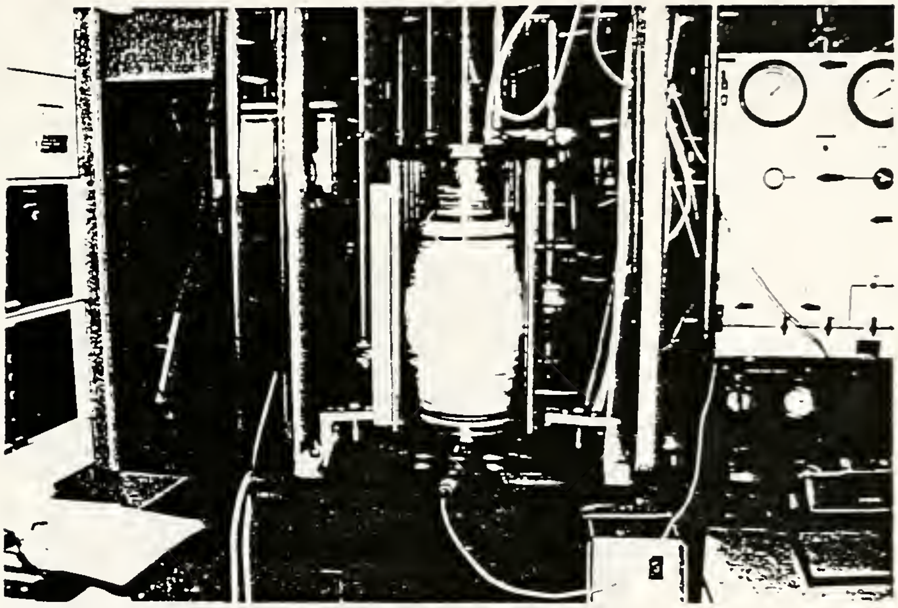


Figure 6.24 A rubber-sand sample - an example of failure by symmetrical bulging

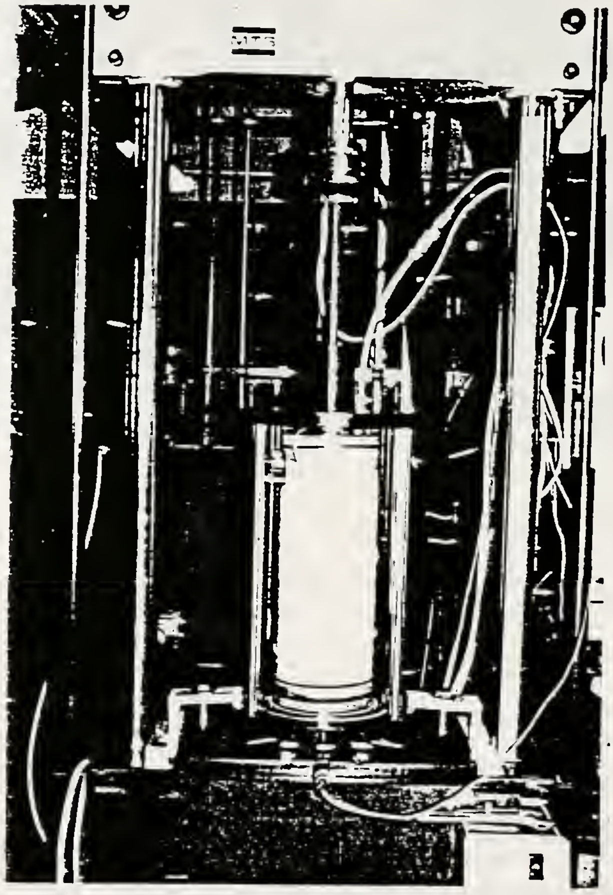


Figure 6.25 A rubber-soil sample during triaxial compression test - an example of vertical compression with little lateral spreading at high confining pressure

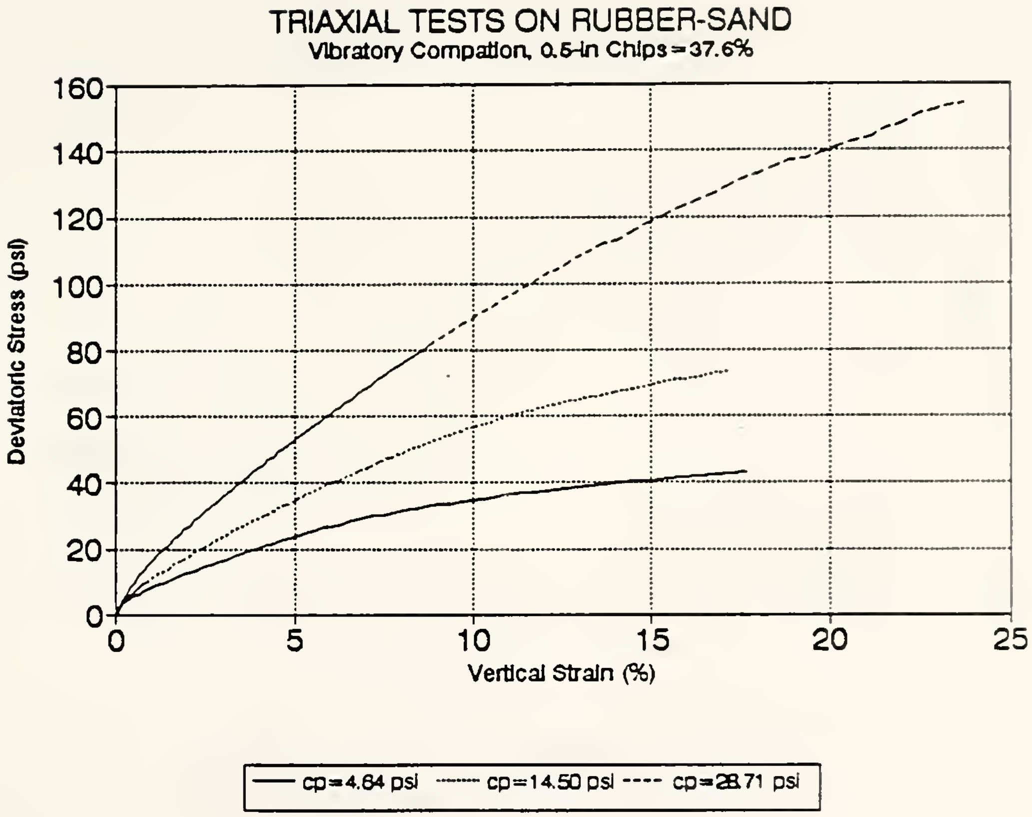


Figure 6.26 Triaxial compression test on rubber-sand with 0.5-in chips at optimum chip/mix ratio (≈ 38%)

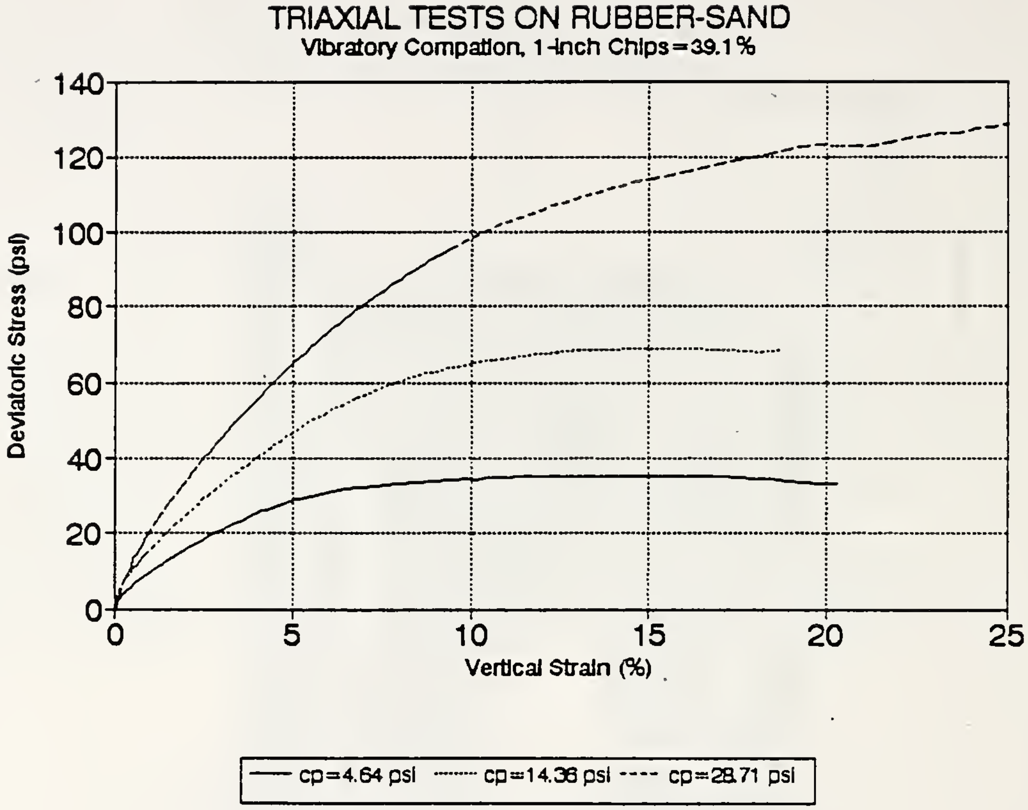


Figure 6 .27 Triaxial compression test on rubber-sand with 1-in chips at optimum chip/mix ratio (≈ 39%)

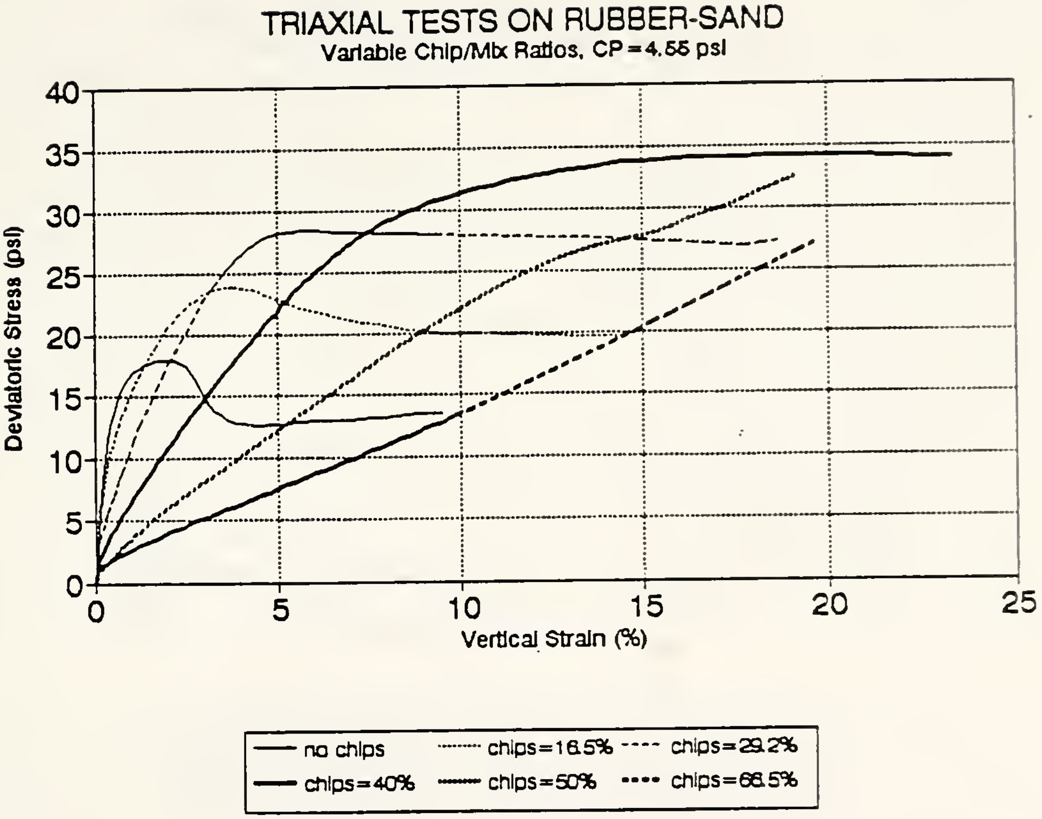


Figure 6.28 Triaxial compression tests on rubber-sand with variable chip/mix ratios, at low confining pressures (≈4.5 psi)

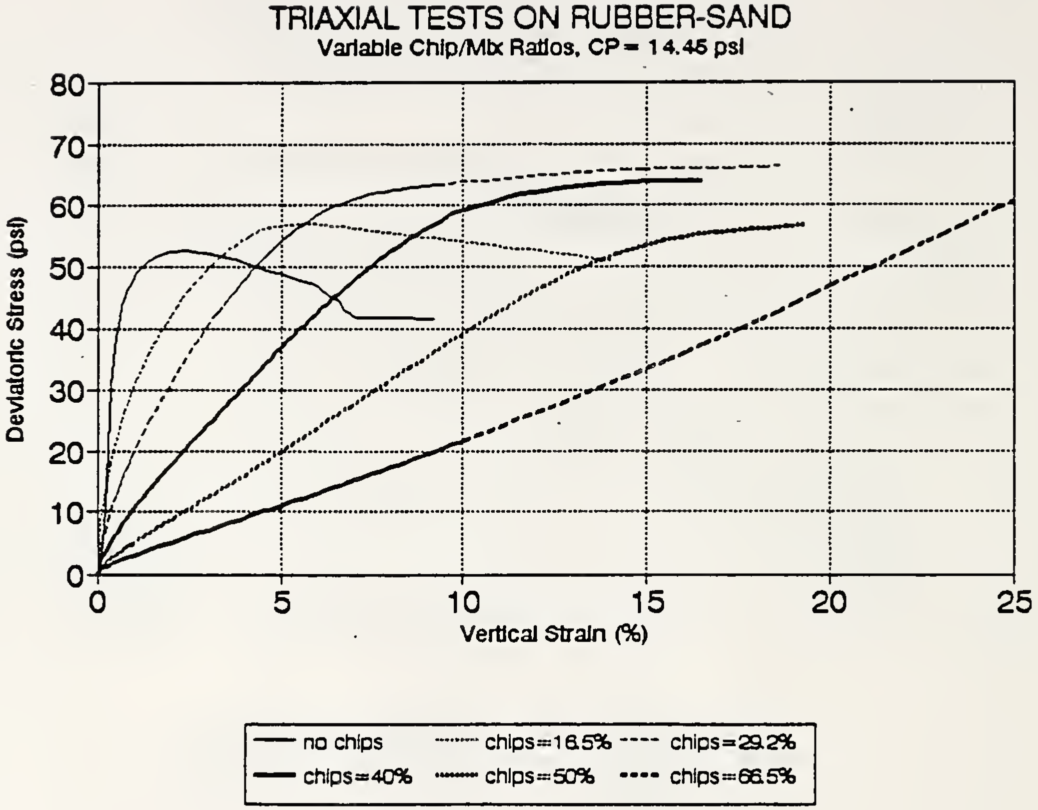


Figure 6.29 Triaxial compression tests on rubber-sand with variable chip/mix ratios, at medium confining pressures (≈14.5 psi)

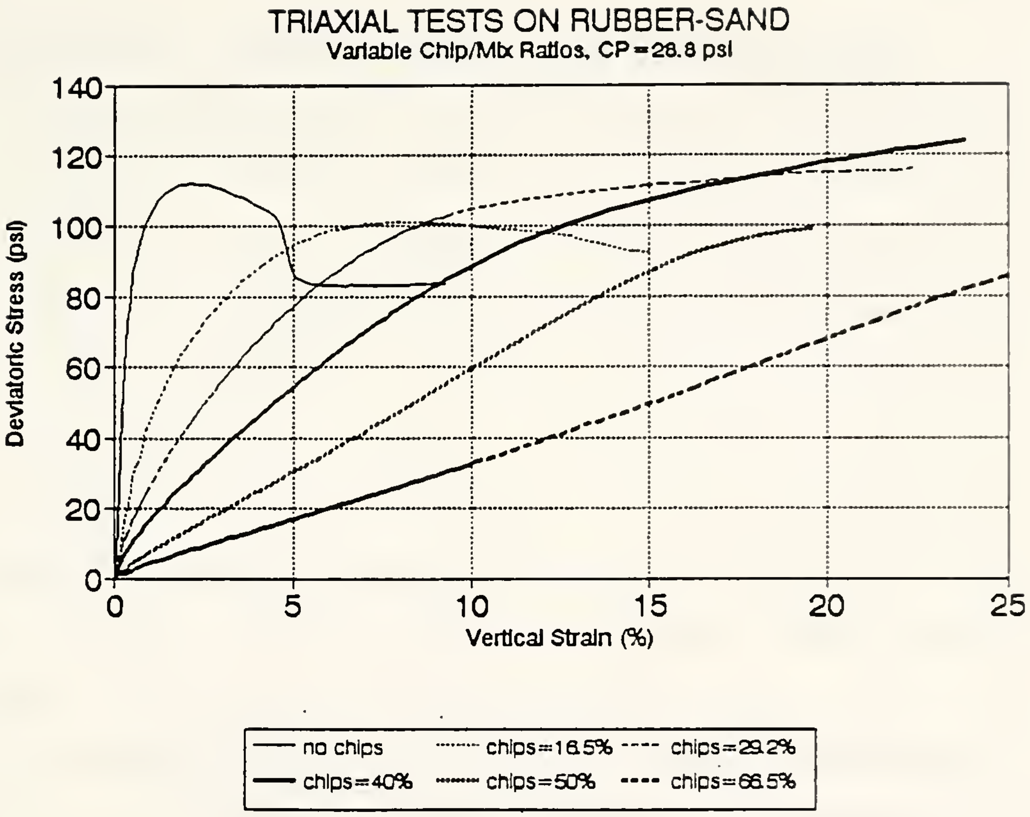


Figure 6.30 Triaxial compression tests on rubber-sand with variable chip/mix ratios, at high confining pressures (≈29 psi)

with increasing chip/mix ratio is less compared to that at low confining stresses. This implies that sand fill with tire chips will show a maximum benefit from the reinforcing properties of tire chips at low to medium confining stresses.

Figures 6.31 to 6.33 compare the data from samples with no chips and rubber-sand mixes varying from 29 to 40%. It is found that the samples of rubber-sand with 1-inch chips yield deviatoric stress values which are close to those obtained from the rubber-sand samples with 29% chips. The rubber-sand samples with 0.5-inch chips yield generally lower values of deviatoric stress than samples with 1-inch chips at corresponding strain levels (also see Table 6.2). The reinforcing effect of chips on the stress-strain curves of rubber-sand is very evident from curves plotted in Figures 6.31 and 6.32. It is also clearly observed from Figure 6.33 that the addition of chip does not contribute much to the rubber-sand mix at higher confining stresses.

6.6.3 Shear Behavior of Rubber-Crosby Till

Figures 6.34 through 6.38 plot the curves for triaxial compression tests on rubber-Crosby till with varying chip/mix ratios for three levels of confining pressures, i.e., 4.5, 14.5, and 28.9 psi. Similar to the stress-strain behavior of rubber-sand, the rubber-Crosby till samples also show behavior which is similar to that of Crosby till at low

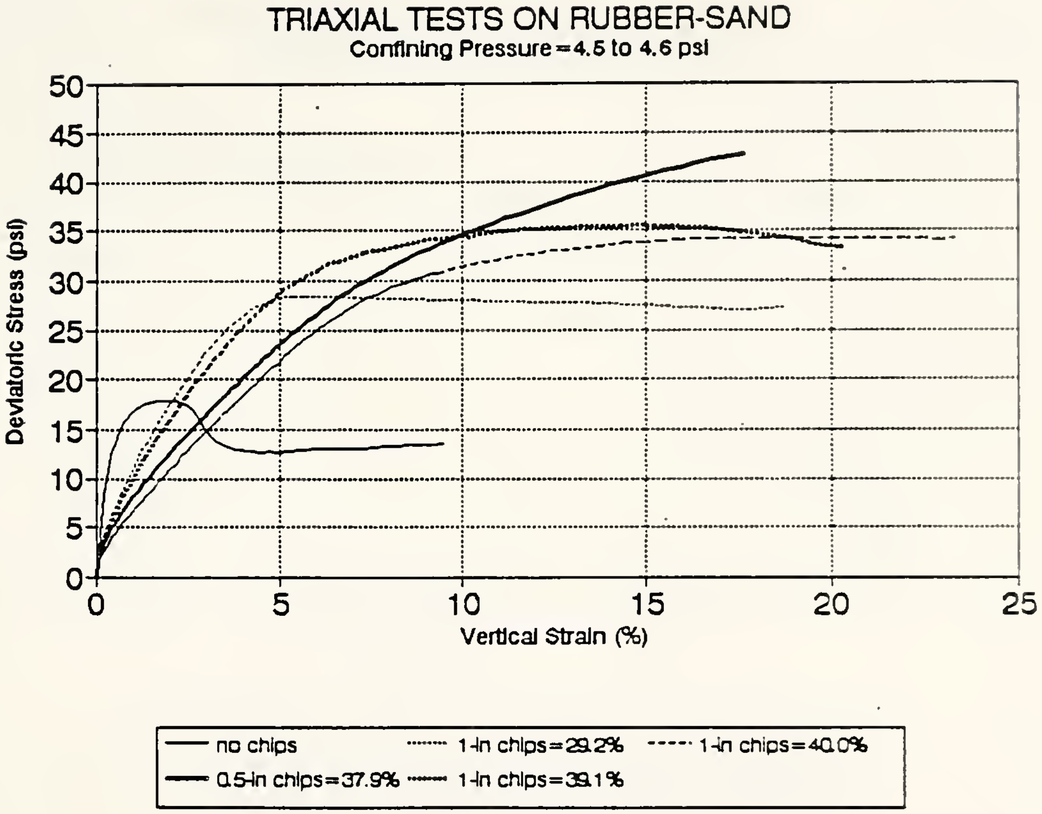


Figure 6.31 Triaxial compression tests on rubber-sand having optimum chip/mix ratio (≈39%), at low confining pressures (≈4.5 psi)

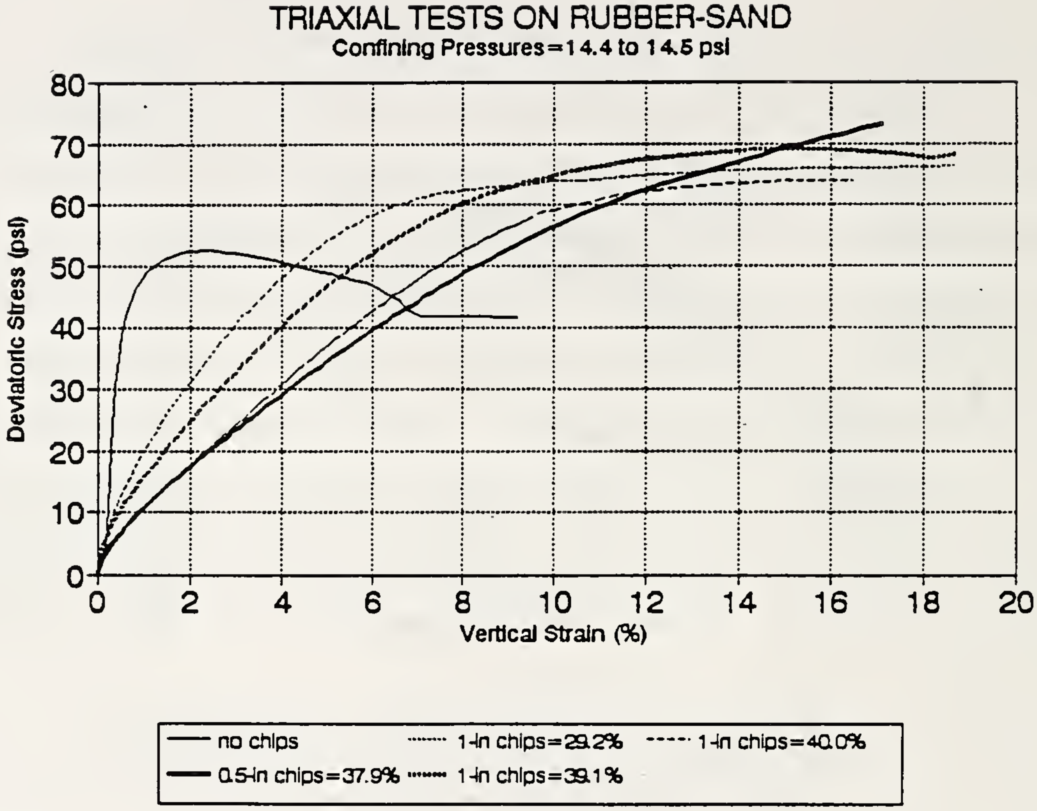


Figure 6.32 Triaxial compression tests on rubber-sand having optimum chip/mix ratio (≈39%), at medium confining pressures (≈14.5 psi)

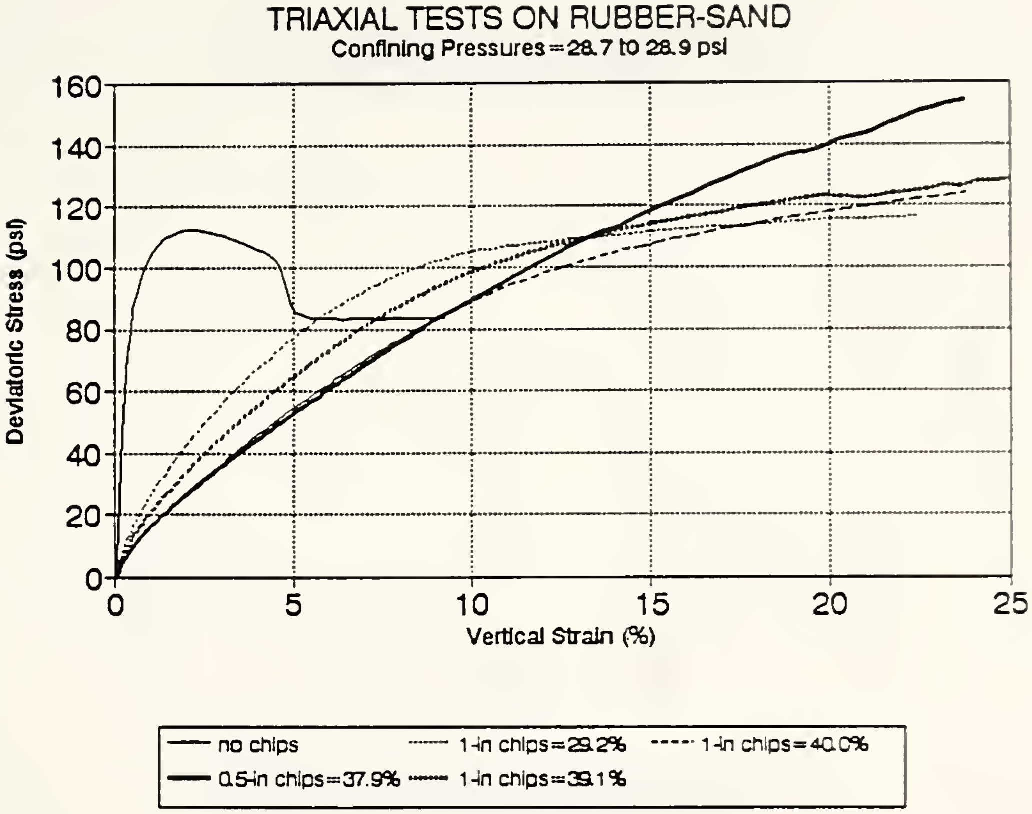


Figure 6.33 Triaxial compression tests on rubber-sand having optimum chip/mix ratio (≈39%), at high confining pressures (≈28.8 psi)

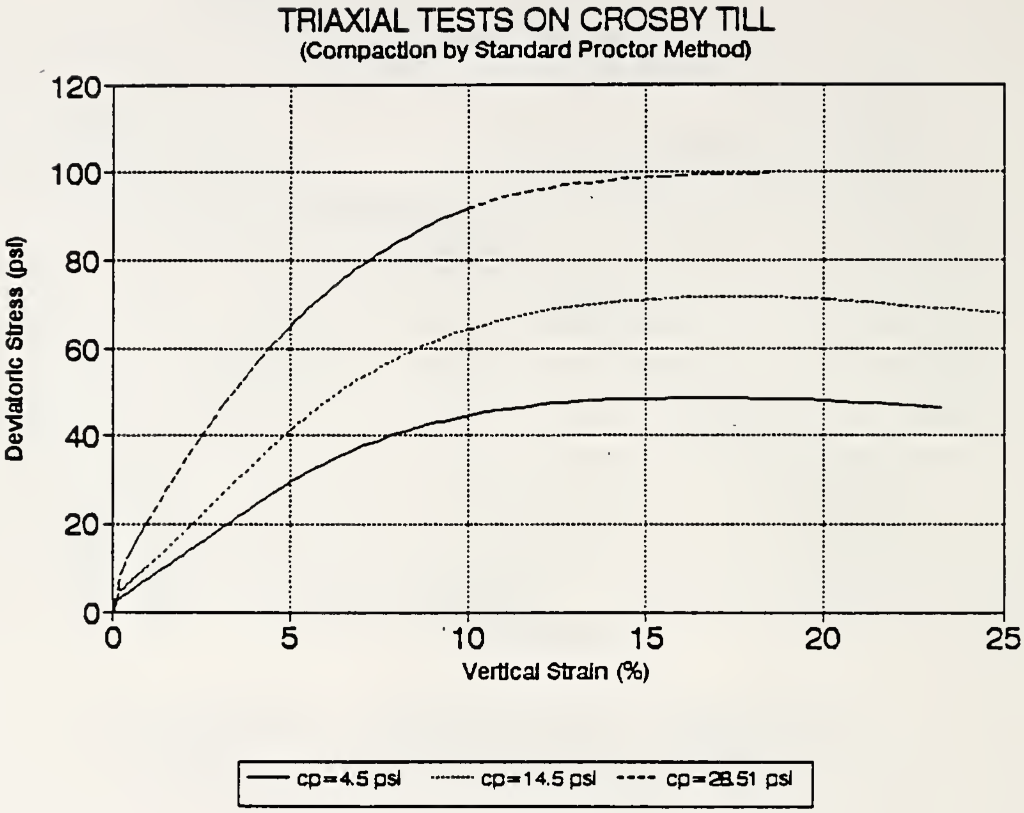


Figure 6.34 Triaxial compression tests on Crosby till

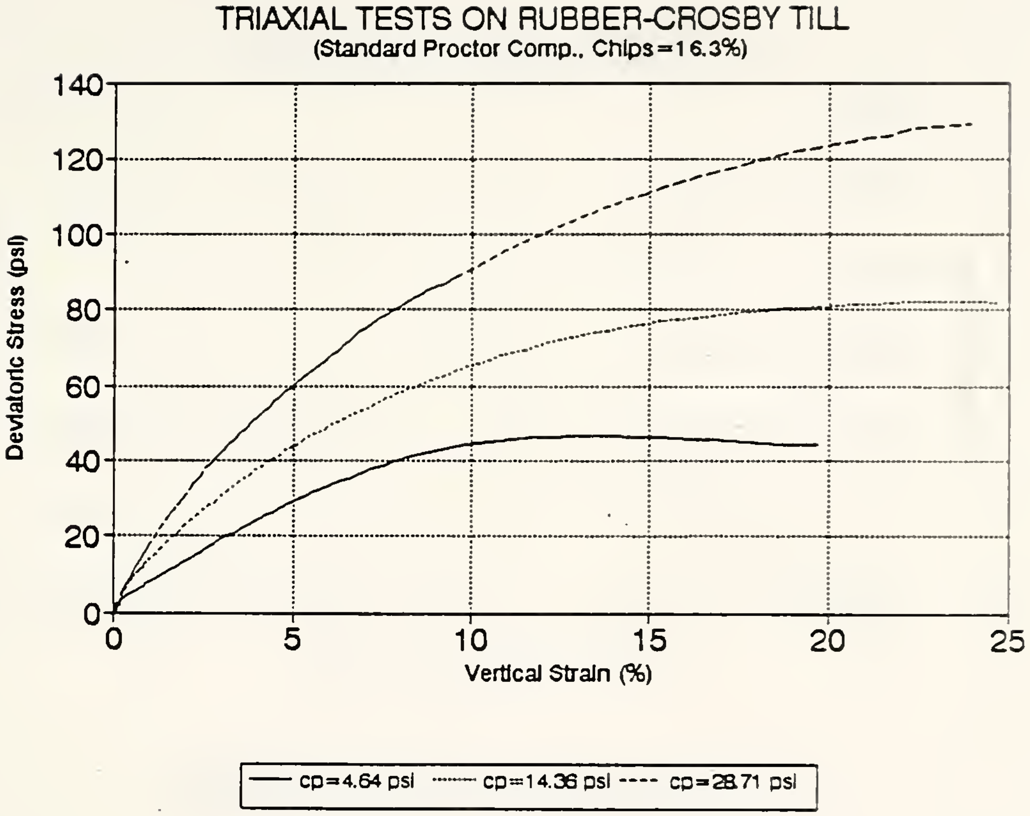


Figure 6.35 Triaxial compression tests on rubber-Crosby till with chip/mix ratio equal to 16.3%

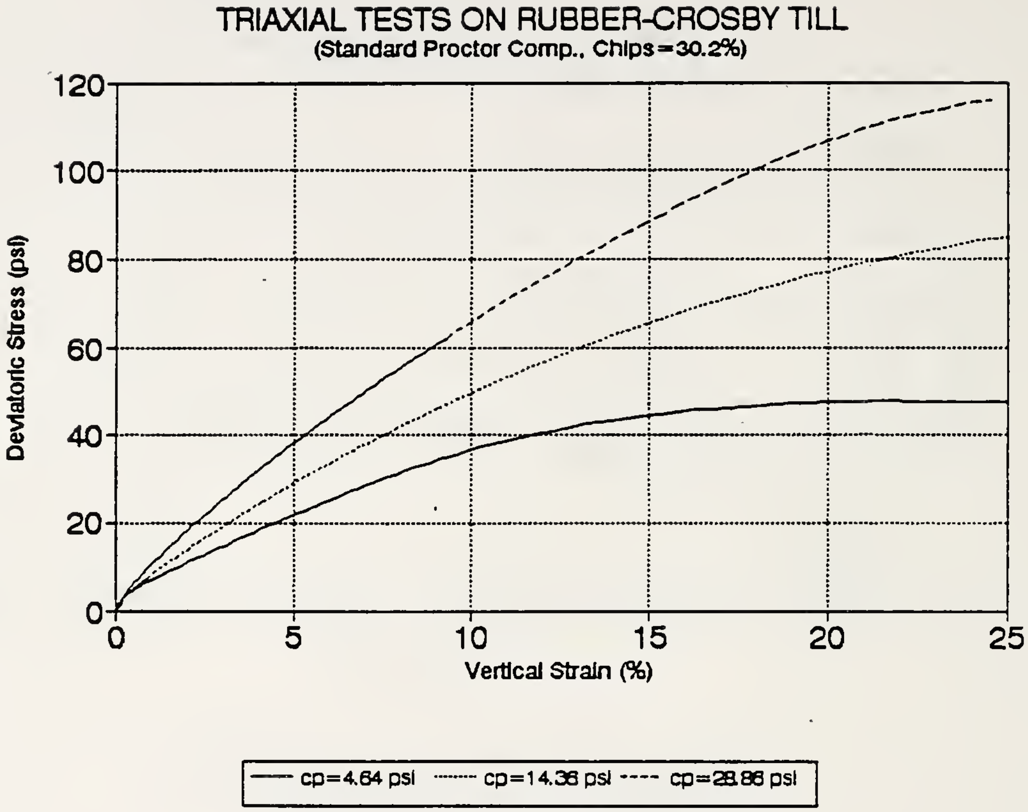


Figure 6.36 Triaxial compression tests on rubber-Crosby till with chip/mix ratio equal to 32.2%

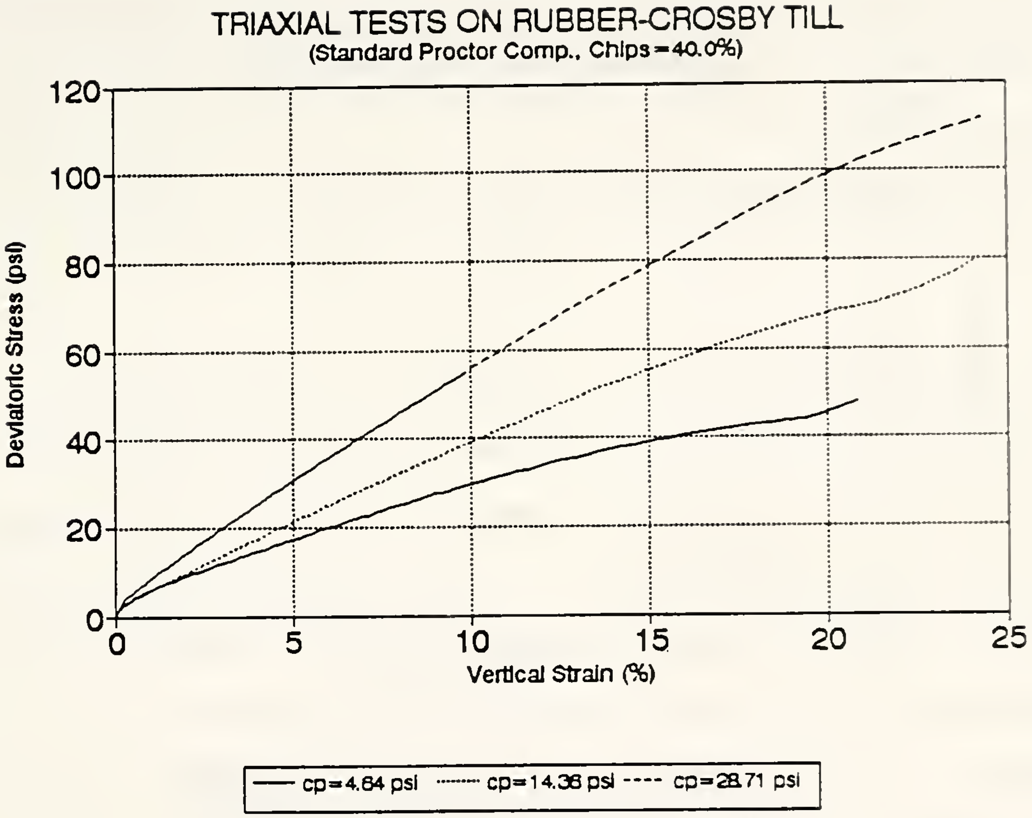


Figure 6.37 Triaxial compression tests on rubber-Crosby till with chip/mix ratio equal to 40.0%

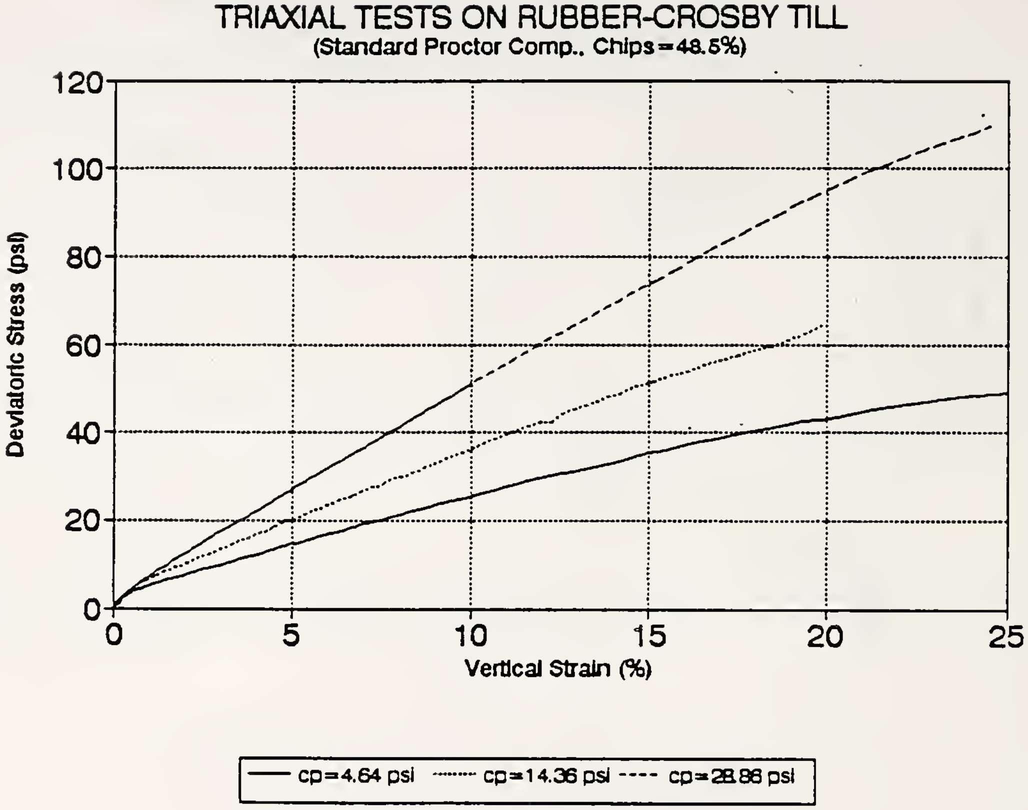


Figure 6.38 Triaxial compression tests on rubber-Crosby till with chip/mix ratio equal to 48.5%

chip/mix ratios and it changes to that of tire chips alone at higher chip/mix ratios. Confining pressures, as expected, have pronounced influence on the stress-strain behavior of rubber-Crosby till, the deviatoric stress increasing with increasing confining stresses. Figure 6.39 plots data from rubber-Crosby mix with 0.5-inch chips. The values of deviatoric stress reached in the case of various confining pressures are lower than those for rubber-sand mix with 1-inch size chips (also see Table 6.3).

Figures 6.40 to 6.42 compare the stress-strain curves from various triaxial compression tests performed on samples with varying chip/mix ratios. The curves demonstrate that unlike rubber-sand mixes, tire chips do not contribute towards increase in the strength of rubber-Crosby mixes. Instead, the samples show somewhat lesser stiffness compared to soil without tire chips, thus resulting in increased strain at failure. Figures 6.43 to 6.45 plot the data from triaxial tests on rubber-Crosby mix with chip/mix ratios varying from 30 to 40%. The curves show that rubber-Crosby mixes with smaller size chips show lower deviatoric stress than rubber-Crosby mixes with larger size chips at corresponding strain levels. Figures 6.46 plots the data from triaxial compression tests on rubber-Crosby till samples prepared using variable compactive efforts. The curves indicate that compactive effort has a small effect on the

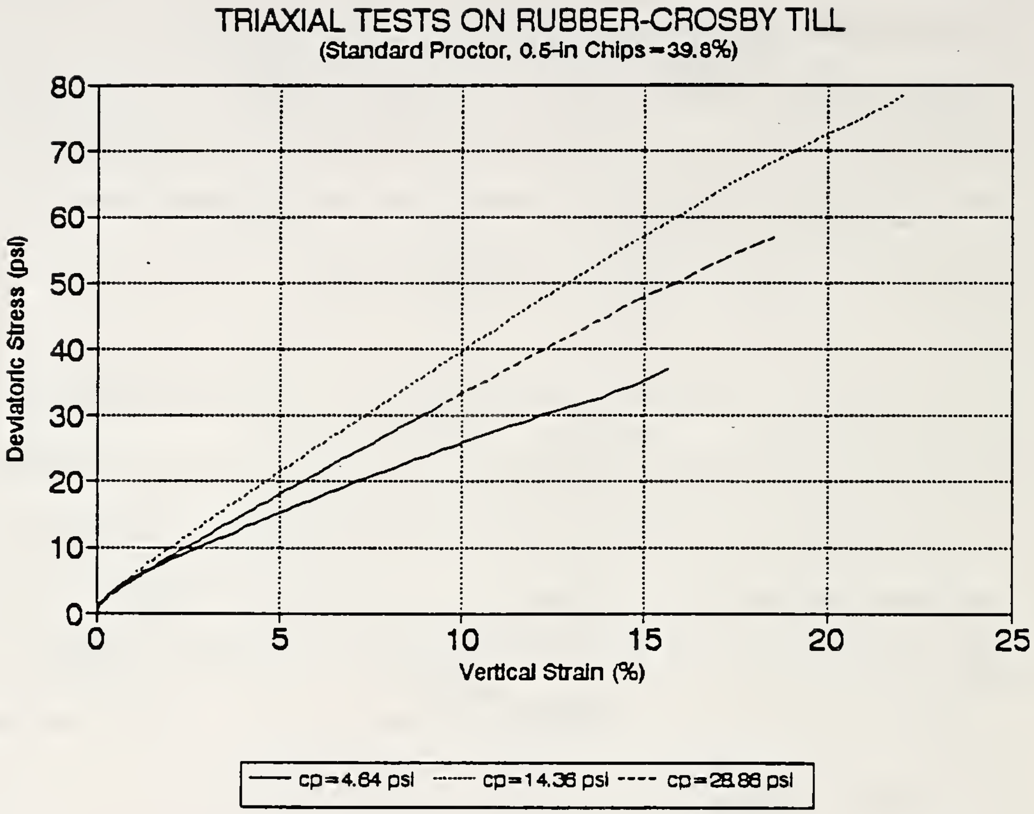


Figure 6.39 Triaxial compression tests on rubber-Crosby mix having chip size equal to 0.5 inch

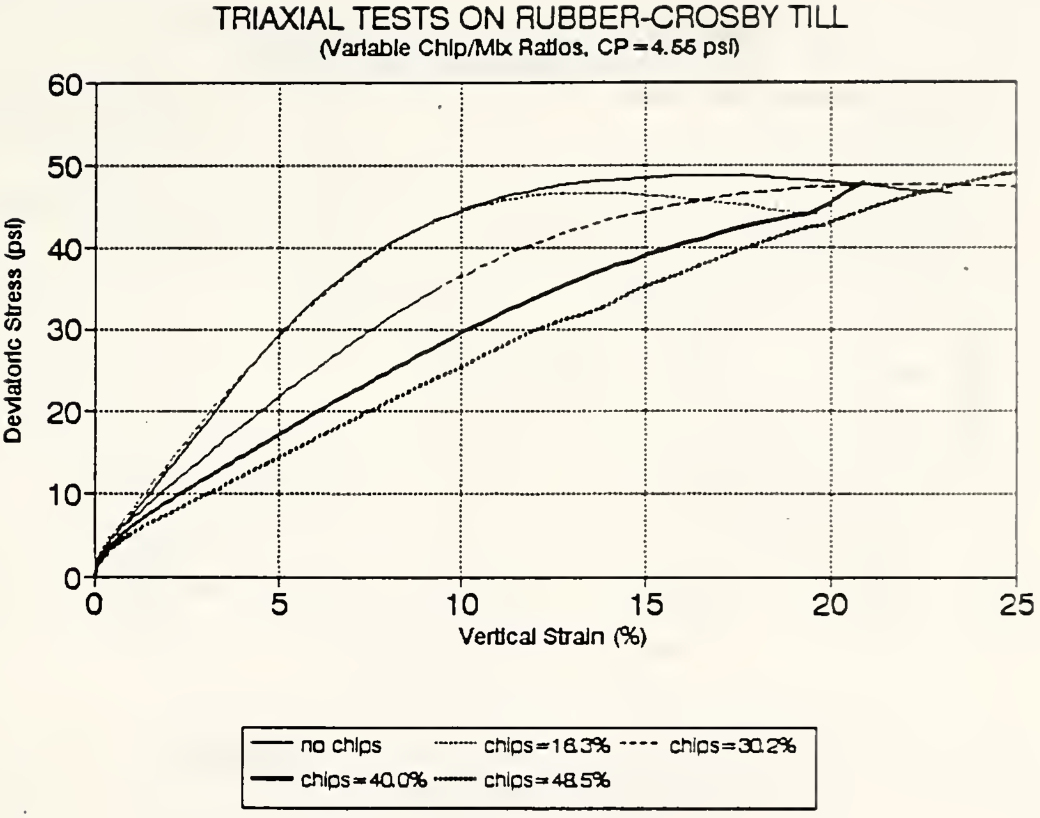


Figure 6.40 Triaxial compression tests on rubber-Crosby till with variable chip/mix ratio, at low confining pressures (≈ 4.5 psi)

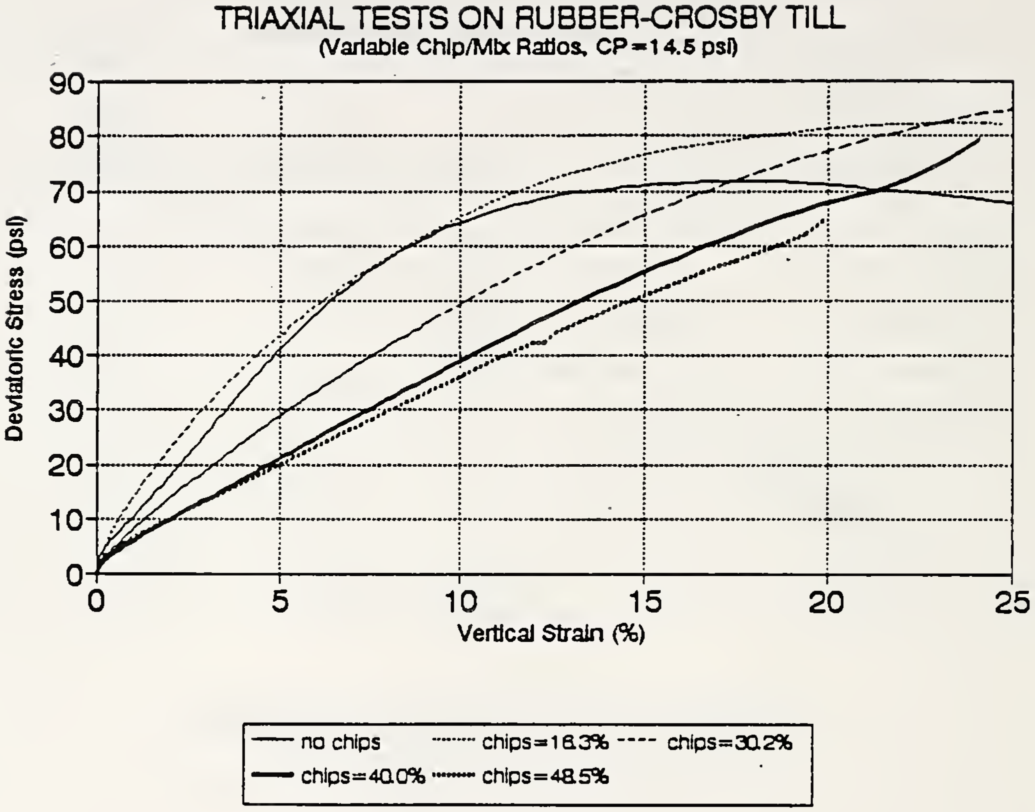


Figure 6.41 Triaxial compression tests on rubber-Crosby till with variable chip/mix ratio, at medium confining pressures (≈ 14.5 psi)

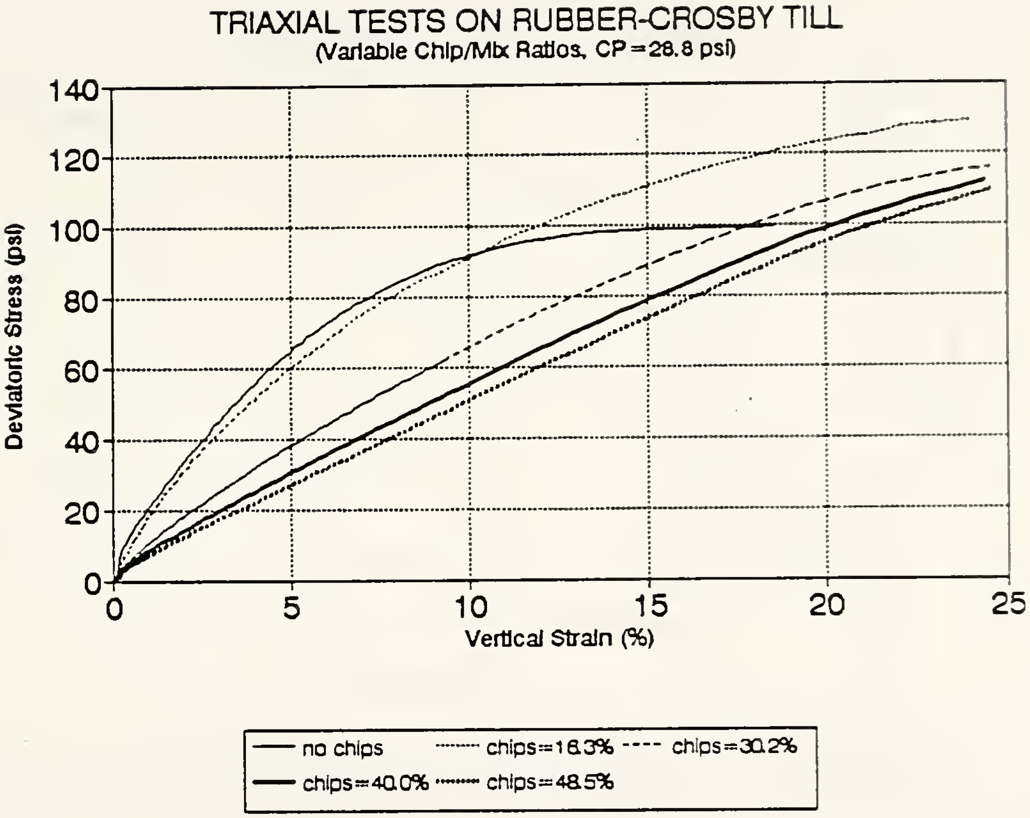


Figure 6.42 Triaxial compression tests on rubber-Crosby till with variable chip/mix ratio, at high confining pressures (≈ 28.8 psi)

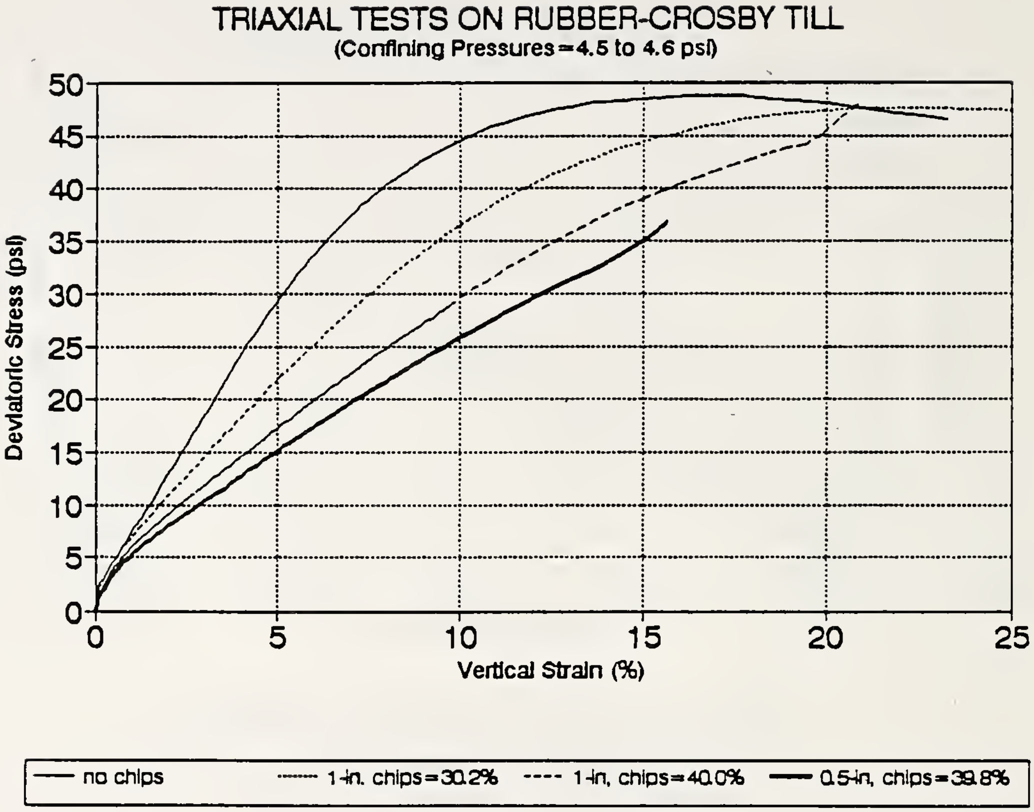


Figure 6.43 Triaxial compression tests on rubber-Crosby till with optimum chip mix ratio (≈ 39%), at low confining pressures (≈4.5 psi)

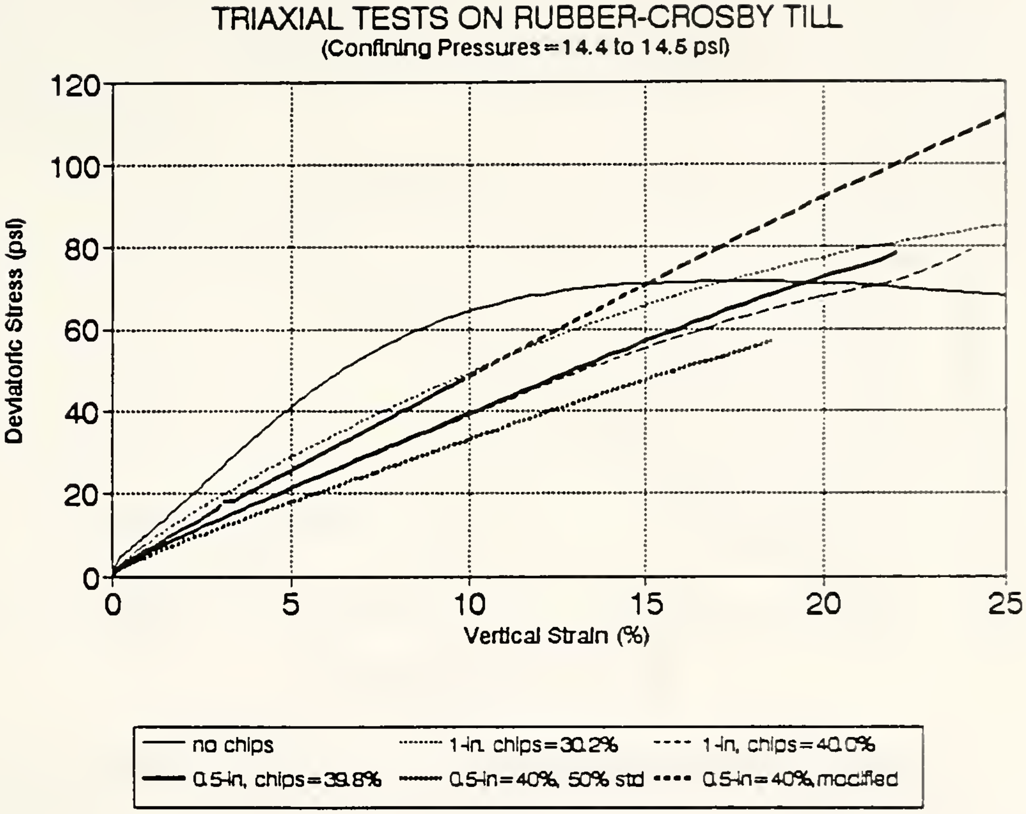


Figure 6.44 Triaxial compression tests on rubber-Crosby till with optimum chip mix ratio (≈ 39%), at medium confining pressures (≈14.5 psi)

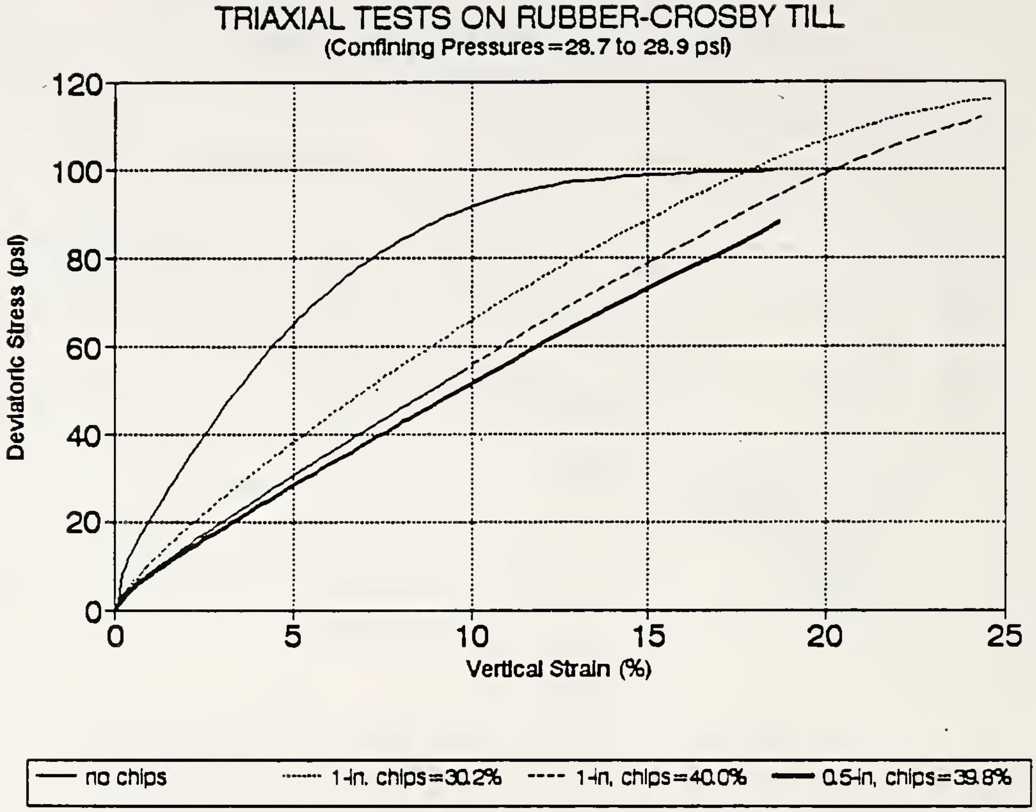


Figure 6.45 Triaxial compression tests on rubber-Crosby till with optimum chip mix ratio (≈ 39%), at high confining pressures (≈28.8 psi)

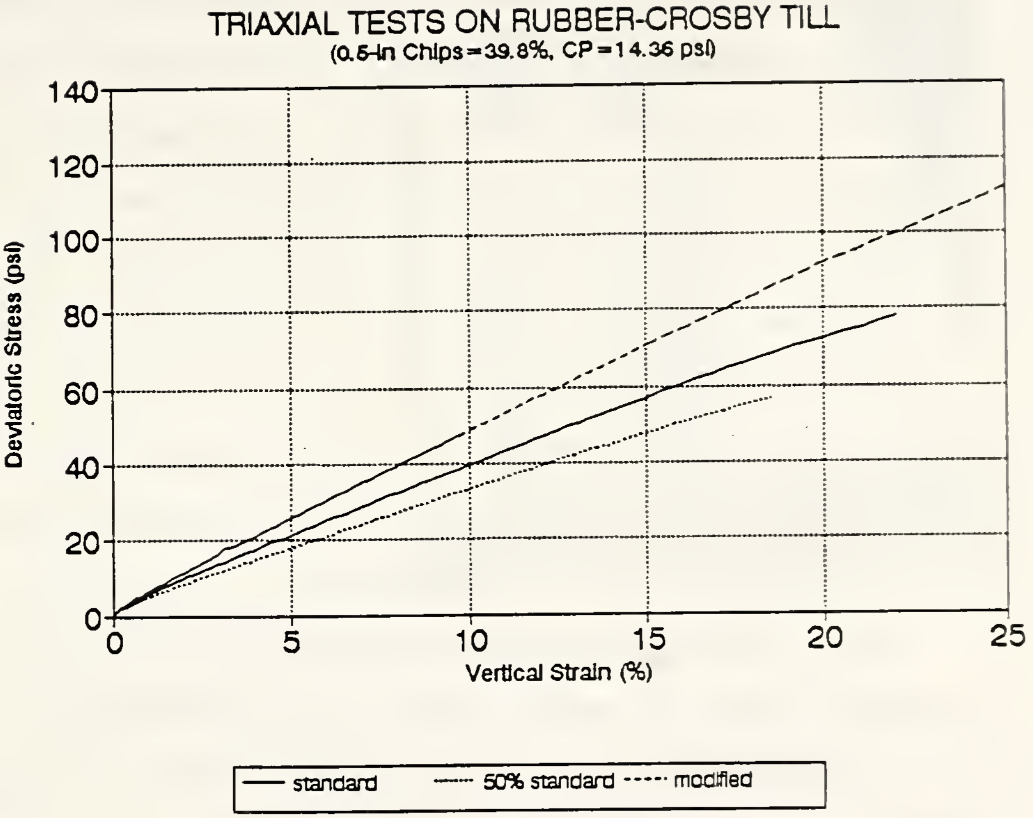


Figure 6.46 Triaxial compression test on rubber-Crosby mix with 0.5-in chips size and samples prepared using variable compactive effort

strength of rubber-Crosby mixes (see Figures 6.47 to 49 for rubber-Crosby samples prior, during, and after shear).

6.6.4 Strength Parameters for Rubber-Soils

The stress-strain behavior of rubber-soils demonstrate that the samples of tire chips and rubber-soil mixes with percent chips greater than 15% fail by symmetrical bulging and not on a single shear plane. Such samples do not show a clear peak strength and do not fail by yielding. The samples strain harden and the stiffening of the sample continuously increases with increasing strains. Thus in classic sense the sample never fails. It is, therefore, imperative to define the failure in order to determine the strength parameters.

Geotechnical engineers are familiar with the concept of the Mohr-Coulomb strength envelope. In designing, usually the allowable strains are selected and then corresponding stresses are determined. The allowable stresses vary depending upon many factors, including: importance of structure, function of structure; differential settlements of foundation soils; the level of accuracy of determining the stress-strain relationships; and anticipated changes in the structures due to environmental factors. In the absence of any clear peak strength in the case of rubber-soils, the strength parameters may be computed using a criterion of allowable strains.

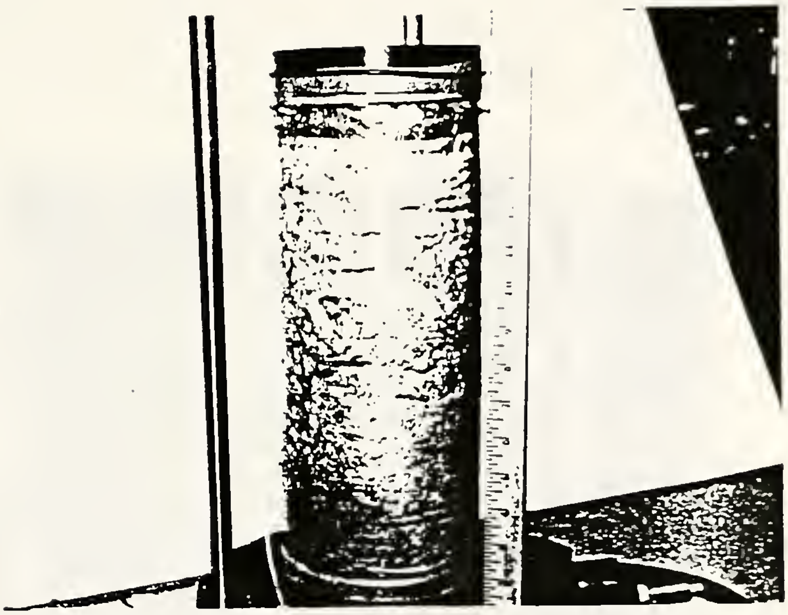


Figure 6.47 A rubber-Crosby sample prior to shear

Figure 6.48 A rubber-Crosby sample during shear

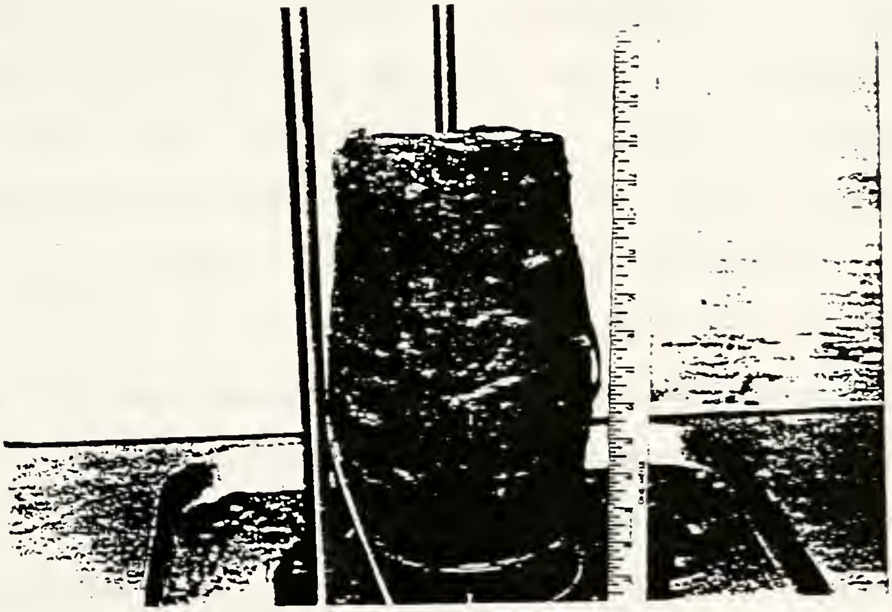
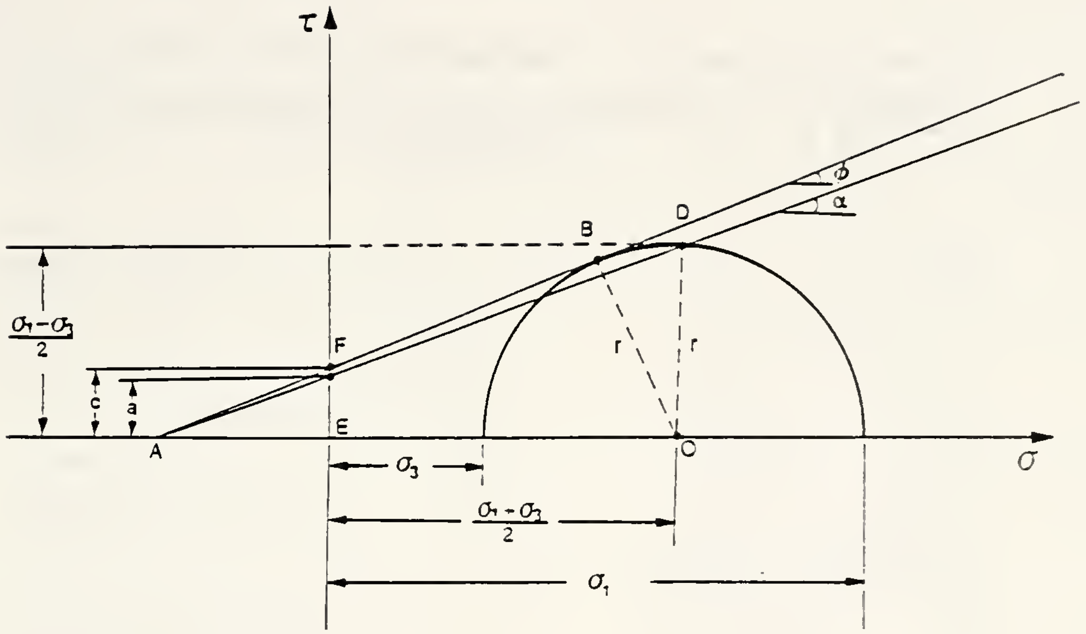


Figure 6.49 A rubber-Crosby sample after shear

Holtz (1989) reports that little information is available on tolerable settlements of highway embankments. However, it has been documented (NCHRP, 1971) that post construction settlements during the economic life of a roadway of as much as 1 to 2 ft. are generally considered tolerable provided they: 1) are reasonably uniform; 2) do not occur adjacent to a pile supported structure; and 3) occur slowly over a long period of time. Cox (1985) reports that 20% strain is often used as the allowable strain in embankment design. It is evident that the strength parameters depend on the choice of allowable strains.

To determine the effect of allowable strains on the strength parameters of rubber-soils and to select optimum strain levels for defining strength parameters for design and evaluations of embankments incorporating tire chips, the author selected four levels of axial strains. To avoid constructing Mohr-Coulomb envelopes and determining the strength parameters graphically, simple relationships between parameters a, tan α, c, and ϕ_d were used. The relationships are routinely used in geotechnical engineering and are derived in Figure 6.50.

Tables 6.4 to 6.6 summarize the basic test information and strength parameters based on the criterion of allowable strains for tire chips, rubber-sand, and rubber-Crosby till, respectively. The strength parameters for tire chips



$\Delta AOD \qquad \overline{AO} = \frac{r}{\tan\alpha}$

$\Delta AOB \qquad \overline{AO} = \frac{r}{\sin\varphi}$

$$\overline{AO} = \frac{r}{\tan\alpha} = \frac{r}{\sin\varphi}$$

$$\sin\varphi = \tan\alpha$$

$$\varphi = \sin^{-1}(\tan\alpha) \qquad \text{———} \qquad (6.5)$$

$\Delta AEF \qquad \overline{AE} = \frac{c}{\tan\varphi} = \frac{a}{\tan\alpha}$

$$c = \frac{a\tan\varphi}{\tan\alpha} = a \cdot \frac{\tan\varphi}{\sin\varphi} = \frac{a}{\cos\varphi}$$

$$c = \frac{a}{\cos\varphi} \qquad \text{———} \qquad (6.6)$$

Figure 6.50 Derivation of equation for determination

Table 6.4 Strength parameters for tire chips.

Test No.	Size of Chips (in.)	Compaction	Dry Density (pcf)	Strain Levels (%)	a (psi)	tan (α)	r^2	c (psi)	ϕ [4] (°)
TPC01	1.00	Modified	42.33	5	2.46	0.1303	0.9967	2.48	7.49
TPC02	1.00	Modified	42.85	10	3.46	0.2472	0.9975	3.57	14.31
TPC03	1.00	Modified	43.73	15	4.50	0.3372	0.9998	4.78	19.71
				20	5.16	0.4173	0.9999	5.68	24.66
TPC04	1.00	Standard	40.39	5	2.13	0.1446	0.9824	2.15	8.31
TPC05	1.00	Standard	41.13	10	3.11	0.2526	0.9897	3.21	14.63
TPC06	1.00	Standard	40.68	15	3.73	0.3470	0.9935	3.98	20.30
TPC07 TPC08	1.00 1.00	Standard Standard	41.57 40.45	20	4.36	0.4277	0.9976	4.82	25.32
TPC09	1.00	50% Standard	40.10	5	2.07	0.1700	0.9997	2.10	9.79
TPC10	1.00	50% Standard 50% Standard	40.35	10	3.60	0.2173	0.9999	3.69	12.55
				15	4.51	0.3024	0.9997	4.73	17.60
TPC11	1.00		40.26	20	4.99	0.3854	0.9997	5.41	22.67
TPC12	0.50	Standard	39.99	5	1.92	0.1200	0.9998	1.94	6.89
TPC13	0.50	Standard	39.05	10	3.23	0.1949	0.9995	3.29	11.24
TPC14	0.50	Standard	39.00	15	4.17	0.2737	0.9989	4.34	15.88
				20	4.86	0.3495	0.9986	5.19	20.46

Notes:
1. Modified = Modified Proctor Energy = 56,250 ft-lb/ft^3
2. Standard = Standard Proctor Energy = 12,375 ft-lb/ft^3
3. 50% Standard = 50% of Standard Proctor Energy = 6,188 ft-lb/ft^3
4. See Figure 6.50 for definition & relationship between a, tan(α), c, tan(ϕ)

Table 6.5 Strength parameters for rubber-sand

Test No.	Size of Chips (in.)	Chip/mix ratio (%)	Confining Pressure (psi)	Strain Levels (%)	a (psi)	tan α	r^2	c (psi)	ϕ (°)
TRS01	No-Chip	0	4.50	5	-0.24	0.6615	0.9998	0	41.41
TRS02	No-Chip	0	14.36	10	-	-	-	-	-
TRS03	No-Chip	0	28.86	15	-	-	-	-	-
TRS04	1.00	16.5	4.64	5	2.17	0.6006	0.9996	2.71	36.91
TRS05	1.00	16.5	14.50	10	1.05	0.6252	0.9998	1.35	38.70
TRS06	1.00	16.5	28.86	15	-	-	-	-	-
TRS07	1.00	29.16	4.50	5	5.52	0.4944	0.9943	6.35	29.63
TRS08	1.00	29.16	14.50	10	3.04	0.6110	0.9992	3.34	37.66
TRS09	1.00	29.16	28.86	15	2.65	0.6286	0.9993	3.41	38.95
TRS10	1.00	40.00	4.64	5	5.15	0.3957	0.9988	5.61	23.31
TRS11	1.00	40.00	14.36	10	5.13	0.5413	0.9972	6.10	32.77
TRS12	1.00	40.00	28.86	15	4.09	0.6013	0.9999	5.12	36.96
TRS13	1.00	50.00	4.64	5	-0.68	0.3562	0.9601	0.00	20.37
TRS14	1.00	50.00	14.36	10	4.54	0.4362	0.9988	5.05	25.86
TRS15	1.00	50.00	28.71	15	3.84	0.5519	0.9986	4.60	33.50
TRS16	1.00	66.54	4.50	5	2.23	0.1699	0.9999	2.26	9.73
TRS17	1.00	66.54	14.36	10	1.89	0.3324	0.9901	2.00	19.41
TRS18	1.00	66.54	28.71	15	4.91	0.3759	0.9992	5.30	22.08
TRS19	0.50	37.85	4.64	5	5.26	0.3891	0.9998	5.71	22.90
TRS20	0.50	37.85	14.50	10	5.48	0.5383	1.0000	6.50	32.57
TRS21	0.50	37.85	28.71	15	4.42	0.6238	0.9998	5.66	38.59
TRS22	1.00	38.78	4.64	5	6.55	0.4299	0.9964	7.25	25.46
TRS23	1.00	39.32	14.36	10	5.17	0.5684	0.9985	6.28	34.64
TRS24	1.00	39.37	28.71	15	4.08	0.617	0.9999	5.18	38.10

Notes:
1. All samples are prepared by using vibratory compaction
2. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent
3. See Figure 6.50 for relation between a, c, tan α and ϕ .

Table 6.6 Strength parameters for rubber-Crosby till

Test No.	Size of Chips (in.)	Chip ratio (%)	Confining Pressure (psi)	Strain Levels (%)	a (psi)	tan α	r^2	c (psi)	φ (°)
TRC01	No-Chip	0	4.50	5	6.14	0.4299	0.9970	6.80	25.46
TRC02	No-Chip	0	14.50	10	9.28	0.4914	1.0000	10.66	29.43
TRC03	No-Chip	0	28.71	15	9.72	0.5099	0.9996	11.30	30.66
				20	9.58	0.5151	0.9996	11.18	30.00
TRC04	1.00	16.27	4.64	5	7.43	0.3873	0.9979	8.06	22.79
TRC05	1.00	16.27	14.36	10	6.21	0.5810	0.9982	7.63	35.52
TRC06	1.00	16.27	28.71	15	7.77	0.5686	0.9992	9.45	34.65
				20	5.71	0.6232	0.9992	7.30	38.55
TRC07	1.00	30.18	44.52	5	6.82	0.2612	0.9991	7.67	15.14
TRC08	1.00	30.18	14.36	10	9.96	0.3740	0.9997	10.74	21.96
TRC09	1.00	30.18	28.86	15	9.88	0.4748	0.9973	11.23	28.35
				20	8.82	0.5460	0.9971	10.53	33.09
TRC10	1.00	40.05	4.64	5	5.50	0.2205	0.9947	5.64	12.74
TRC11	1.00	40.05	14.36	10	7.65	0.3598	0.9990	8.20	21.09
TRC12	1.00	40.05	28.71	15	8.39	0.4543	0.9991	9.42	27.02
				20	8.44	0.5271	0.9999	9.93	31.81
TRC13	1.00	48.49	4.64	5	4.93	0.2025	0.9985	5.03	11.68
TRC14	1.00	48.49	14.36	10	6.69	0.3472	0.9999	7.13	20.32
TRC15	1.00	48.49	28.86	15	7.81	0.4441	0.9999	8.72	26.37
				20	7.92	0.5208	0.9999	9.28	31.39
TRC16	0.50	39.80	4.64	5	6.17	0.1173	0.9980	6.21	6.74
TRC17	0.50	39.80	14.36	10	9.37	0.2181	0.9875	9.60	12.60
TRC18	0.50	39.80	28.86	15	11.07	0.3130	0.9866	11.66	18.24
TRC19	0.50	39.64	14.36						
TRC20	0.50	39.79	14.36						

Notes:
1. Chip ratio is the air dried weight of chips divided by dry weight of mix, expressed in percent
2. See Figure 6.50 for definition & relation between a, c, tan α and φ .

indicate that with increase in allowable strains from 5% to 20% the values of c and ϕ_d vary from about 2.5 to 5.7 psi and angle ϕ_d from 7.5 to 25.5°. Similarly, for rubber-sand at optimum chip/mix ratio (i.e., ≈ 39% 1-inch chips by weight of dry mix), the value of c and ϕd vary for strain levels ranging from 5 to 15% from 7.5 to 5.3 psi and 25.5 to 38.1°, respectively (see Table 6.5). The range of strength parameters for rubber-Crosby mixes at 40% 1-inch chips by weight of dry mix vary from c = 5.6 to 9.4 psi to ϕd = 12.7 to 27° for strain levels varying from 5 to 15% (see Table 6.6).

6.7 Comparison with the Previous Research

Table 6.7 compares the values of strength parameters for soils and tire chips reported in the literature with those obtained from triaxial compression testing of rubber-soils. The results of the author for shear testing of soils and chips compare very well with those published in the literature. The author is unaware of any results published in the literature about shear parameters for rubber-soil mixes. However, a comparison of results from rubber-soils with those for tire chips alone and with soils with no chips, as well as the experience of the author gained during testing of these materials, leads the author to conclude that the strength parameters obtained and summarized in Tables 6.4 to 6.7 are reasonable and accurate. It is proposed that they

Table 6.7 Range of engineering properties for conventional fill and rubber-soils

Material	Dry Density (pcf)	Strength Intercept (psi)	Values of φ (°)	Reference/ Remarks
Poorly graded clean sand, sand-gravel mix (SP)	100-120	-	37	Hunt (1986)
Medium sand, angular:				Leonards (1962)
Loose	-	-	32-34	
Dense			44-46	
Sand, angular grains, well graded:	-	-		Peck, et al. (1974)
Loose			33	
Dense			45	
Mixture of inorganic silt and clays, as compacted (CL-ML)	100-120	9.4	32	Peck, et al. (1974)
Tire Chips, 2-in. sq.in 6-in. dia. triaxial compression test	38.04	3.75	21	Bressette (1984)
Tire chips, 2-in. shredded in 6-in. dia. triaxial compression test	37.93	4.58	14	Bressette (1984)
Tire chips of 3-in max. size in direct shear test at 10% strain	21-31	0.63-1.67	19-25	Humphrey, et al. (1992)
1-in. chips, compacted with std. Proctor energy at:				Author (Table 6.4)
Strain = 10%	40.84 ±0.45	3.2	14.6	
Strain = 15%		4.0	20.3	
Strain = 20%		4.8	25.3	
1-in. chips and Ottawa sand mix:		-	41.4	Author (Table 6.5)
sand only, no chips	115.58 ±0.20			
Chip/mix ratio=39%:				
Strain = 5%		7.3	25.5	
Strain = 10%	88.82 ±0.40	6.3	34.6	
Strain = 15%		5.2	38.1	
1-in. chips & Crosby till				Author (Table 6.6)
no chips @ 10% strain	119.30 ±0.27	10.7	29.4	
Chip/mix ratio = 40%:				
Strain = 5%	81.18 ±0.17	5.6	12.7	
Strain = 10%		8.2	21.1	
Strain = 15%		9.4	27.0	

may be used for design and also evaluation of embankments incorporating similar materials, until such time as more extensive testing results are available.

6.8 Summary and Conclusions

A number of triaxial compression tests were performed on rubber-soils for determining the feasibility of using tire chips in highway embankments as lightweight geomaterials. Tire chips of different sizes and gradations and two types of soils (see Chapter 4 for the properties of testing materials) were tested in the laboratory using a 6-inch diameter triaxial apparatus. The variables considered included: type of soils, method of sample preparation, size of chips, ratios of tire chips/mix, and confining pressures. The results are summarized in Tables 6.1 to 6.7. The data are also presented graphically in Figures 1 to 34.

The following salient conclusions are drawn based on a critical evaluation of the test results:

- Unlike soils, the samples of tire chips do not fail by yielding or have a single shear plane, instead the samples exhibit a strain hardening behavior and continuously become stiffer with increased axial straining. The chip specimens at low confining pressures demonstrate symmetrical bulging. The specimens sheared at high confining pressures compress vertically, with little lateral spreading, and continue to become stiffer even at large strains, when the capacity of the apparatus is reached. Confining pressure is the most important factor effecting the strength of chips. Size of chips and compactive efforts do not significantly effect the shear behavior of tire chips. However, a trend of increasing deviatoric stresses with increase in chip sizes and compactive effort is observed.

- The shear behavior of rubber-sand is mainly effected by the level of confining pressures and chip/mix ratios. Higher confining pressures yield higher strength values. The rubber-sand samples exhibit behavior similar to that of sand at low chip/soil ratios and similar to that of chips at high chip/soil ratios. Compactive effort and chip size has little effect on shear behavior of rubber-sand. Tire chips have a reinforcing effect on rubber-sand mixes. The increase in strength is a maximum at chip/soil ratio of about 39% at low to medium confining pressures (≈ 4 to 20 psi), which is considered an optimum ratio for rubber-sands for use as lightweight geomaterials..
- Similar to rubber-sands, the rubber-Crosby mixes exhibit stress-strain behavior similar to Crosby

till at low chip/mix ratios and like chips alone at higher chip/soil ratios (>20% chips by the dry weight of mix). Unlike rubber-sand, tire chips do not have an appreciable reinforcing effect on the behavior of Crosby till. The inclusion of tire chips in Crosby till reduces the deviatoric stress values compared to those of soil alone at corresponding strain levels and increases the strain at failure. The compactive effort and size of chips do not significantly effect the stress-strain behavior of rubber-Crosby.

- The failure criterion for rubber-soils is to be based on allowable strains instead of peak or yielding strength. Strength parameters for rubber-soils for 5, 10, 15, and 20% strain levels have been determined and summarized in Tables 6.4 to 6.6.

CHAPTER 7

RESILIENT MODULUS TESTING OF RUBBER-SOILS

7.1 Introduction

The deflection and deterioration of road surfaces are mainly related to the deformation of underlying soils. The American Association of State Highway and Transportation Officials (AASHTO) Guide for Design and Pavement Structures (1986) recommends the resilient modulus as the material property for characterizing elastic deformation of soils due to repeated loading. Considerable interest is being shown by the highway community in developing a broad database for understanding the resilient behavior of subgrade soils and evaluating the influence of environmental effects and other factors like state of stress, initial density, and gradation on the resilient modulus of subgrade soils.

Recently, a comprehensive study on "Subgrade Resilient Modulus for Pavement Design and Evaluation" has been concluded at Purdue University, West Lafayette, Indiana (Lee, et al. 1993). The study documents resilient modulus test data for five fine-grained soils and one coarse-grained soil typically found in Indiana. They have developed simplified design procedures for the prediction of as-compacted and in-service resilient modulus, based on unconfined compression tests. They have also considered the influence of environmental factors on the design value of resilient modulus.

The intent of this research is to evaluate the effect of incorporating tire chips on the resilient behavior of subgrade soils. Resilient modulus of two types of soils, one coarse-grained and one fine-grained, has been determined at different chip/mix ratios (see Chapter 4 for the properties of test soils and the characteristics of tire chips). Subsequent sections of this chapter contain: a description of the testing equipment and an outline of testing procedures, testing program, and a discussion on the results from resilient modulus testing of rubber-soils. Finally, a summary of salient conclusions from this study is given at the end of this chapter.

7.2 Testing Equipment and Procedures

The resilient modulus tests were conducted using a 4-inch diameter, external chamber triaxial cell. The samples of tire chips and rubber-Crosby were prepared using impact type compaction with energy equivalent to Standard Proctor method. The samples of rubber-sand were prepared by vibratory method of compaction using an electromagnet, vertically vibrating table. The samples were enclosed in double rubber membranes and set up in triaxial cell chamber after measuring diameter, height, and weight (see Figures 7.1 and 7.2).

The equipment used for the resilient modulus testing includes: MTS Soil Testing System loading frame with hydraulic power supply unit, a controlling and conditioning unit, an oscilloscope for monitoring the input and output stress pulse, and a personal computer which controls the test and performs data acquisition system. The test is fully automated, after the initial set-up (see Figures 7.3 and 7.4). The reader is referred to Lee, et al. (1993) for a detailed description of testing equipment and software used for resilient modulus testing and data acquisition.

The resilient modulus test was performed according to the procedures described in AASHTO T274-82 (1986), "Standard Method of Test for Resilient Modulus of Subgrade Soils," In summary, a repeated axial deviator stress of fixed magnitude, duration, and frequency is applied to a prepared and conditioned cylindrical test sample. During and between the dynamic deviator stress applications, the sample is subjected to a static all-round stress provided by means of a triaxial pressure chamber. The resilient (recoverable) axial strain response of the specimen is measured and used to compute the

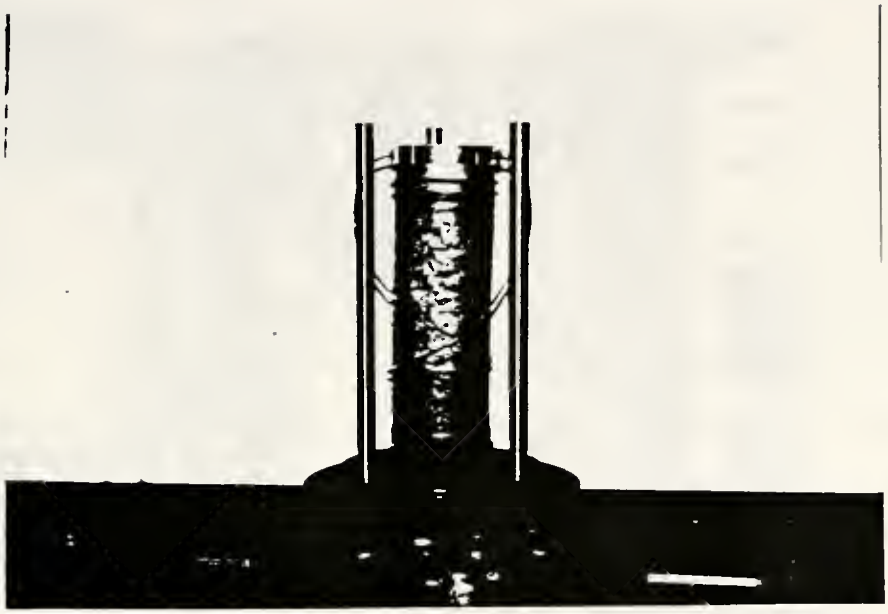


Figure 7.1 A 4-inch diameter rubber-sand sample for resilient modulus testing

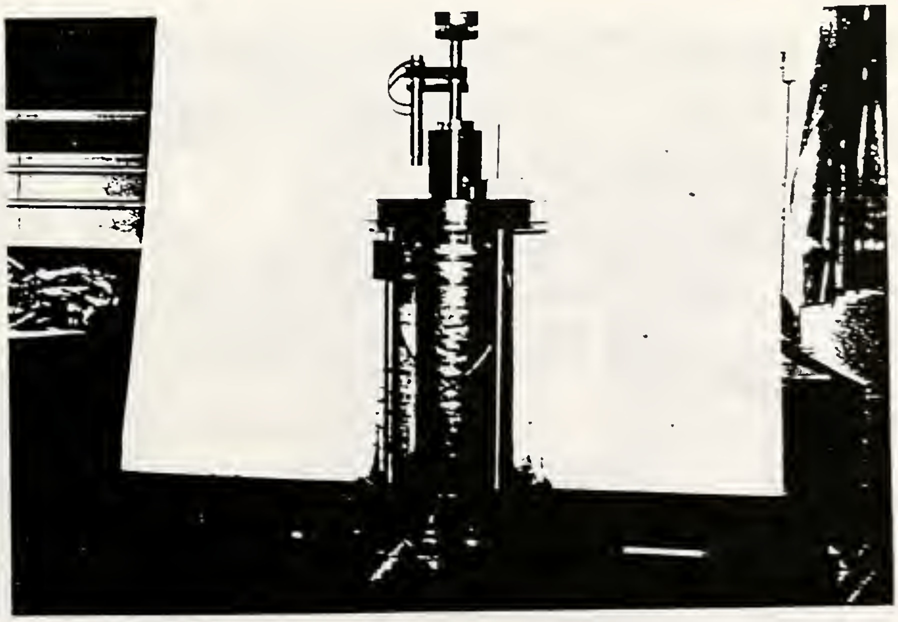


Figure 7.2 A 4-inch diameter rubber-sand sample set up in triaxial chamber for resilient modulus testing

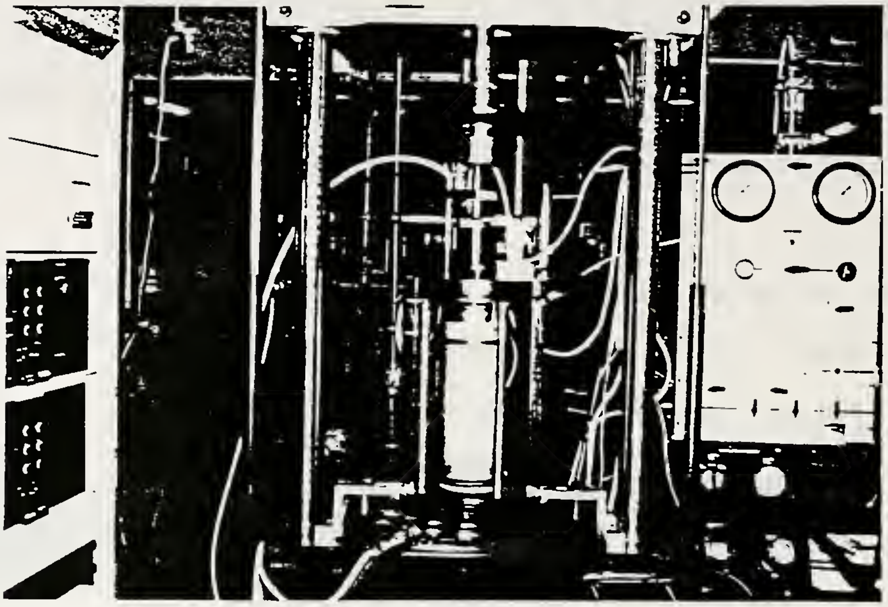


Figure 7.3 A rubber-sand sample set up in the loading frame of MTS Soil Testing System for resilient modulus test

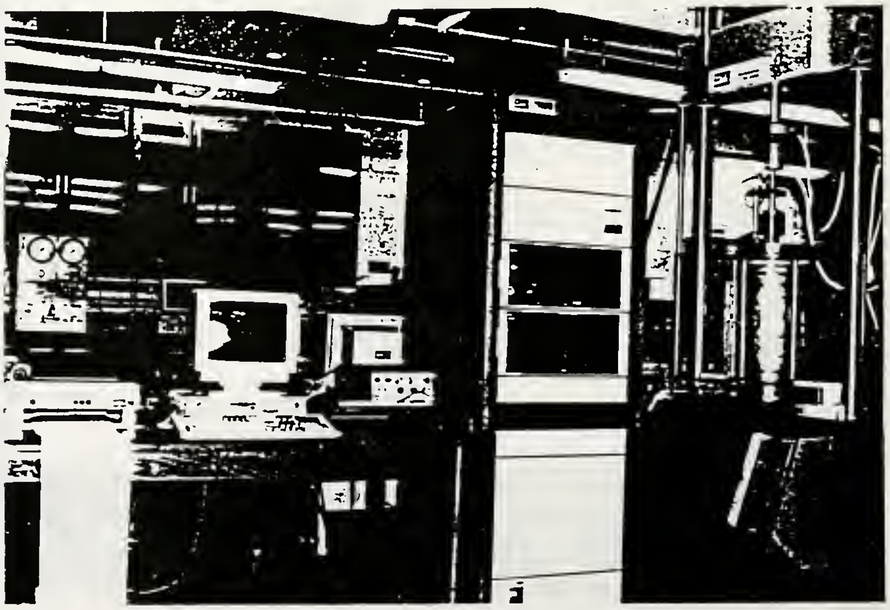


Figure 7.4 A resilient modulus test on rubber-sand in-progress

dynamic stress-dependent resilient moduli.

7.3 Testing Program and Presentation of Results

The influence of traffic on the behavior of compacted rubber-soils is ascertained by conducting resilient modulus tests. A testing program was developed to determine the resilient modulus values for tire chips and subgrade soils. Two types of soils were tested, Ottawa sand and Crosby till. Two sizes of tire chips, i.e., 0.5-inch and 0.75-inch, were selected keeping in mind the size of the available triaxial cell. The chip/mix ratios were varied from 0 to 100%.

The basic information concerning the resilient modulus tests conducted for this research are summarized in Table 7.1. The data from resilient modulus tests on rubber-soils are also presented graphically in Figures 7.5 to 7.7. The data include: basic test information, desired deviator stress, desired confining pressure, data cycle, calculated deviator stress, calculated resilient strain, calculated gauge length, and resilient modulus. The sample area is corrected using the cylindrical correction (see Chapter 6 for the equation of applying area correction to the triaxial specimen) and the resilient modulus is calculated using the following equation:

$$M_R = \frac{\sigma_d}{\epsilon_r} \qquad (7.1)$$

Where σ_d is the deviator stress and ϵ_r is resilient strain.

7.4 Discussion

Previous studies on resilient modulus of subgrade soils (e.g., Rada and Witczak, 1981 and Lee, et al. 1993) have suggested that the resilient modulus can be expressed in terms of following equation:

$$M_R = A\theta^B \tag{7.2}$$

Where θ is the first invariant of stress $(\sigma_1+\sigma_2+\sigma_3)$, and A and B are constants to be determined experimentally.

The constants A and B of Equation 7.2 are determined by performing a regression analysis on the logarithm of both resilient modulus values, M_R, and bulk stress, θ, obtained from rubber-soils testing. The results from regression analysis are summarized in Table 7.1. The data from resilient modulus testing of rubber-sand are also plotted in Figure 7.5 on log-log plot of resilient modulus and sum of principal stresses. The data indicate that the resilient modulus values decrease with increasing chip/mix ratios. The data show significant scatter, especially for tests containing larger percentages of tire chips (30% or greater). This scatter in the data is also reflected in the values of regression coefficient (r^2) given in Table 7.1. The data in

Table 7.1 Summary of results from resilient modulus testing of rubber-soils

Test No.	Size of Chips (inch)	Method of Sample Preparation	Chip/Mix Ratio (%)	Type of Soil	Constant A	Constant B	r^2
AH01	No Chips	Vibratory	No Chips	Sand	1071.5	0.84	0.95
AH02	0.50	Vibratory	15	Sand	524.8	0.83	0.95
AH03	0.50	Vibratory	30	Sand	269.2	0.90	0.67
AH04	0.50	Vibratory	38	Sand	42.7	1.15	0.89
AH05	0.50	Vibratory	50	Sand	38.9	0.83	0.84
AH06	0.50	Vibratory	100	Sand	36.3	0.55	0.74
AH07	0.75	Vibratory	38	Sand	34.7	1.21	0.92
AH08	No Chips	Standard	No Chips	Crosby Till	3162.3	0.49	0.83
AH09	0.50	Standard	15	Crosby Till	53.7	1.15	0.91
AH10	0.50	Standard	29	Crosby Till	61.7	0.91	0.94
AH11	0.50	Standard	38	Crosby Till	55.0	0.67	0.95

Notes:
1. Constants A & B are the regression constants of Equation 7.2 and r^2 is the coefficient of regression
2. Standard = Standard Proctor Energy = 12,375 ft-lb/ft^3
3. See Chapter 4 for vibratory method of sample preparation

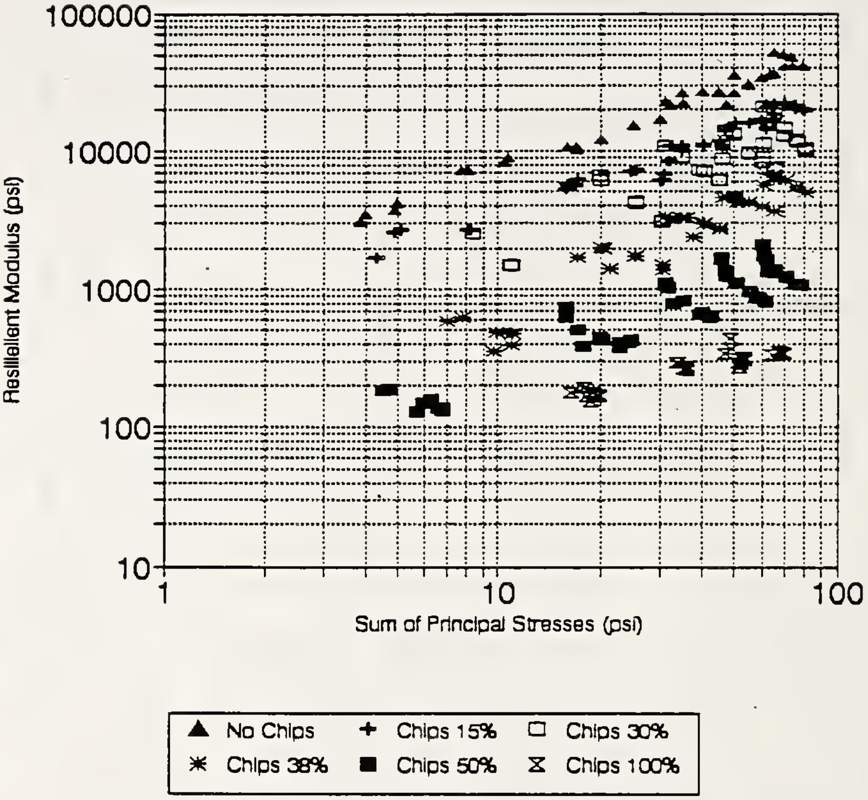


Figure 7.5 Resilient modulus tests on rubber-sand with variable chip/mix ratios

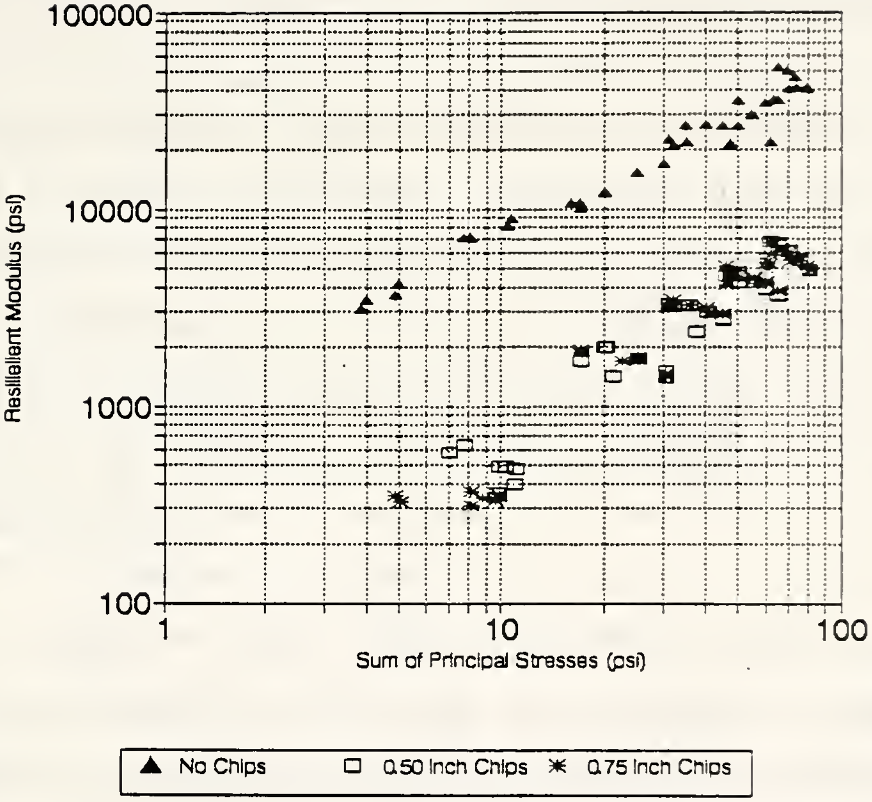


Figure 7.6 Resilient modulus tests on rubber-sand with variable chip sizes

Figure 7.5 indicate a significant reduction in the resilient modulus values of sand samples with addition of tire chips. The reduction in modulus depends on level of confining pressures, deviatoric stress levels, and percent of chips. The modulus decreases with increase in chip/mix ratios.

Figure 7.6 compares the data from tests on rubber-sand of different chip sizes. The data for the two tests with rubber-sand containing chip sizes of 0.5-inch and 0.75-inch and having chip/mix ratios of 38% almost overlap, indicating that the variation in chip size does not influence the resilient modulus values of rubber-sand. However, a comparison of resilient modulus values from tests on Ottawa sand with no chips with results from rubber-sand samples having about 38% chips shows that resilient modulus is decreased substantially by addition of chips to sand. The reduction in modulus may be 80% or even more, depending on the stress levels.

A regression analysis performed on chip/mix ratio, expressed in percent, and constant A parameter for Equation 2 (see Table 7.1) indicates that a correlation exists between the two, which can be used to predict the value of resilient modulus of rubber-sand. The following regression equation was obtained from data on chip/mix varying from 0 to 38% ($r^2 = 0.92$):

$$A = 950 - 21P \qquad (7.3)$$

where P is chip/mix ratio, expressed in percent. The values of B parameter range from 0.83 to 1.15, with a mean of 0.91±0.12 (see Table 7.1). If the value of resilient modulus for sand without chips is known, the value of resilient modulus after addition of chips can be estimated by using Equation 7.2 with values of constants A computed from Equation 7.3 and value of B constant assuming as 0.91. The correlation between regression constant A and chip/mix ratios for Equation 7.2 can also be developed experimentally for any rubber-sand mix.

Figure 7.7 plots the data from resilient modulus tests on rubber-Crosby mixes. The data indicate a significant reduction in the values of resilient modulus with addition of tire chips. The reduction in modulus increases with increase in the chip/mix ratio. Some scatter is also observed in the test data, which is also reflected in the values of regression coefficients summarized in Table 7.1. This scatter is, however, less than that observed in the values of resilient modulus of rubber-sand. The decrease in modulus is also stress dependent. The decrease in modulus values is higher at lower values of confining pressures and deviatoric stress values.

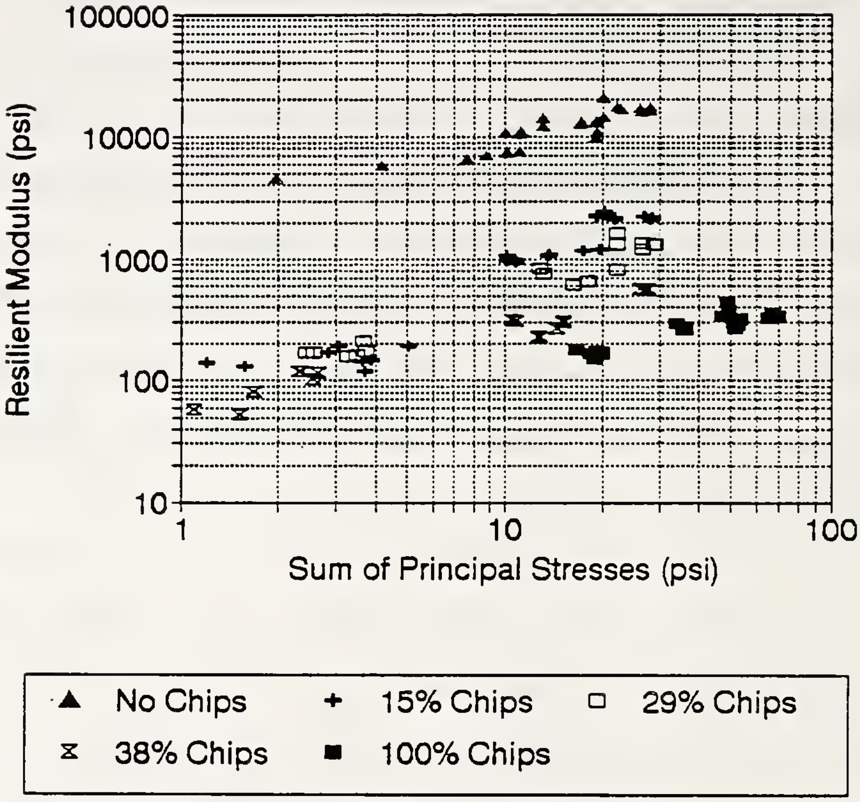


Figure 7.7 Resilient modulus tests on rubber-Crosby till with variable chip/mix ratios

No research study on determination of resilient modulus of rubber-soils could be located by a search of main databases like Compendex Plus, NTIS (National Technical Information Service), TRIS (Transportation Research Information System), and Enviroline. However, a number of studies have been reported in the literature on the resilient modulus of subgrade soils (e.g., Lee, et al.1993; Rada and Witczak, 1981; and Elton and Ray, 1989). The results from resilient modulus tests on soils from this study cannot be compared directly with data from other studies reported in the literature due to variation in many factors, e.g., type of soil, initial dry density, gradation, degree of saturation, etc., which influence the resilient modulus values. A comparison with results from laboratory compacted samples of dune sand reported by Lee, et al., (1993) with results from Ottawa sand indicates a reasonable agreement. However, it is observed that the values of A parameter for the dune sand are higher than those reported by the author for Ottawa sand, and the values of B parameters are comparatively lower. This implies that the resilient modulus values from Ottawa sand are comparatively more effected by the confining stresses.

7.5 Summary and Conclusions

A laboratory testing program has been conducted on tire chips of variable sizes and two test soils, one each from the families of coarse and fine grained soils, to determine the resilient characteristics of rubber-soils. The chip and rubber-Crosby samples were prepared using impact, Proctor type compaction, and the rubber-sand samples by a vibratory method of compaction. The resilient modulus tests were performed on rubber-soils samples with chip/mix ratios varying from 0 to 100%. The tests results have been summarized in Table 7.1 and also plotted in Figures 7.5 to 7.7.

The following salient conclusions are drawn based on a critical evaluations of the test results:

- The resilient modulus of soils decreases with increase in chip/mix ratios. This reduction in modulus is stress dependent and is substantial, up to 80% or even greater depending on the chip/mix ratios and the state of stress. The reduction in modulus is greater for rubber-Crosby than rubber-sand.
- The resilient modulus data from rubber-soils show a significant scatter, greater than that observed for conventional soils. The scatter in data from rubber-Crosby is comparatively lesser than rubber-sands.
- Chip size has no effect on the resilient characteristics of rubber-soils.

- The resilient modulus tests on rubber-soils yield reasonable values for the regression constants of Equation 7.2. The B constant for rubber-sand has a mean value of 0.91 and does not vary much (the variation is ±0.12). A correlation has been found between chip/mix ratios, in percent, and constant A (see Equation 7.3). This regression equation ($r^2=0.92$) can be used to predict the variation in constant A due to addition of tire chips in the sand. If the value of resilient modulus for soils with no chips is known, the values of resilient modulus for rubber-sand with chip/mix ratios of up to 40% can be estimated by using the value of the B constant as 0.91±0.12, and determining the value of the A constant for the desired percent of chip/soil mix using Equation 7.3. The regression constants of Equation 7.2 can also be determined experimentally for accurate estimates of resilient modulus values for rubber-soils.

It is recommended, based on significantly lower values of resilient modulus of rubber-soils compared to conventional subgrade soils, that tire chips alone or mixed with soils, should not be used in the subgrade layer of highway pavements. Rubber-soils are recommended for use in embankments and more than three feet away from asphalt pavement layers, to avoid subjecting asphalt pavements to fatigue stresses, which may cause larger deflection of pavement surfaces under repeated traffic loads and thus affect the service life of such pavements.

CHAPTER 8

PERMEABILITY

8.1 Background

The drainage characteristic of fill materials have pronounced influence on the behavior of embankments and slopes under saturated conditions. A well drained material prevents development of pore pressures during loading of fills and accelerates consolidation of underlying low permeable foundation soil by providing drainage path - thus enhancing the stability of structures. Conversely, a poorly drained material under saturated conditions can cause loss of effective stress due to development of high pore pressures under repeated loads and may also lead to deterioration of subgrades/embankments due to freeze/thaw of water retained in the fill materials. It is, therefore, imperative to determine the hydraulic characteristics of fill materials prior to their use in embankments.

The capacity of a material to transmit water is referred to as permeability, or hydraulic conductivity. There is considerable disagreement as to which term is to be preferred, permeability or hydraulic conductivity. Although, arguments have been put forth in favor of both terms in the literature, much of the confusion can be eliminated by properly defining terms. In this thesis, the expression used for the flow of water through soils is known as Darcy's law:

$$Q = kiA \tag{8.1}$$

Where Q represents a flow rate (L^3/T), i is a dimensionless factor called the hydraulic gradient, A is the gross cross-sectional area of flow (L^2), and k is a factor called the coefficient of permeability (L/T), or Darcy's coefficient of permeability, and herein referred to as permeability.

The value of coefficient of permeability, k, gives the superficial or discharge velocity per unit of gradient, as if the flow occurred through the total volume of the medium, not the void area only. Permeability is the most variable engineering property of soils, with an extremely large range (i.e., from 1 cm/sec for gravel to 10^{-8} cm/sec for clay). It depends on the characteristics of both the permeant and the soil. The void ratio, composition, fabric, and degree of saturation are the major characteristics which govern the permeability of soils (Lambe and Whitman, 1969).

A number of constant head permeability tests have been performed as part of this research on tire chips, alone and also mixed with soils, to determine their suitability as a lightweight geomaterial for use in embankments. This chapter presents the results from permeability testing of rubber-soils. The subsequent subsections contain: a description of testing equipment and procedures; a summary of results from permeability testing of tire chips reported in the literature; presentation of results from this research and a discussion/evaluation of results. Finally, a summary of conclusions is also given at the end of this chapter.

8.2 Testing Equipment and Procedures

An 8-inch diameter, stainless steel mold was used to determine the hydraulic properties of compacted samples of rubber-soils under constant head conditions. An apparatus, originally designed and built by Elsharief (1992) for conducting retention tests to determine filtration characteristics of geotextiles, was suitably modified by the author to perform constant head permeability tests on large size tire chips. The mold can accommodate a sample of up to 9 inch height and the sample can be prepared by impact compaction or using vibratory methods. The head difference applied to the sample can be varied. In addition, a vacuum pump can be used to increase the head difference and accelerate the saturation of the sample. A number of manometers are attached to the permeameter mold to measure the pressure head of water at any height in the soil sample (the permeability mold and the set of manometers is shown in

Figure 8.1). A sample of 6- or 9-inch height is prepared using two methods: impact, Proctor type compaction - for chips and chips/Crosby mix; and vibratory compaction - for chip/sand mix. The mold containing the sample is assembled in the apparatus and the specimen is allowed to saturate from the bottom. Vacuum is applied from the top of the mold in the case of low permeable material to accelerate the saturation. On saturation, the specimen is allowed to equilibrate and achieve steady state conditions for a period which depends on the type of soil or chip/soil mix. The permeability results are computed based on an average flow from ten different readings, to minimize the measurement error.

8.3 Testing Program and Presentation of Results

Permeability tests have been performed on tire chips, alone and mixed with sand and Crosby till (see Chapter 4 for description and properties of test soils). The variables considered include: method of compaction, vibratory and Proctor type; compactive effort, samples were compacted using three levels of compactive energy ; chip sizes, two chip sizes 0.50- and 1-inch; and ratios of chip/soil mix, percent chips varying from 0% to 100%. Samples photographed after the permeability testing are shown in Figures 8.2 to 8.4.

The coefficient of permeability was computed using the

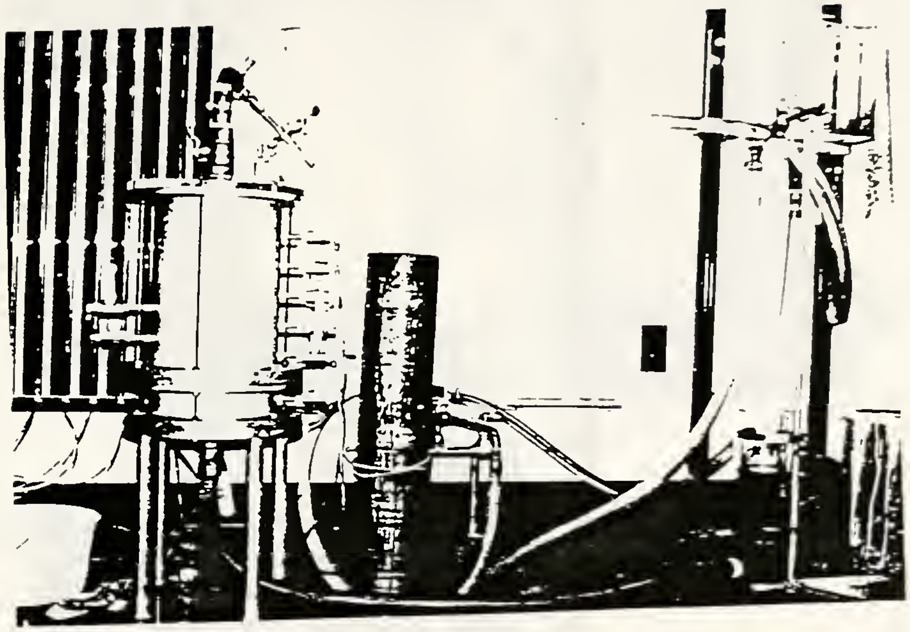


Figure 8.1 An 8-inch diameter permeability mold and set of manometers to measure the pressure head of water

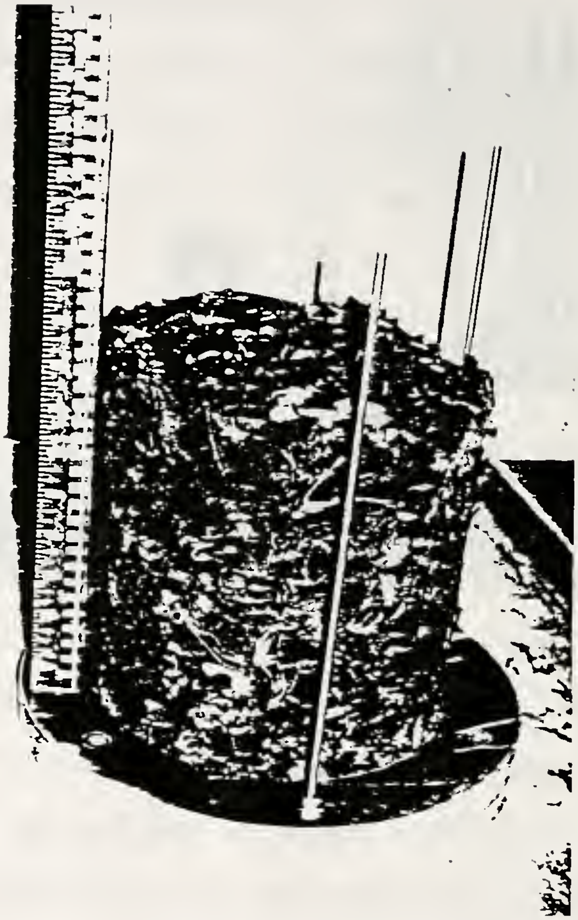


Figure 8.2 A 1-inch size chips sample, photographed after the permeability testing

Figure 8.3 A sample of rubber-sand, photographed after the permeability testing

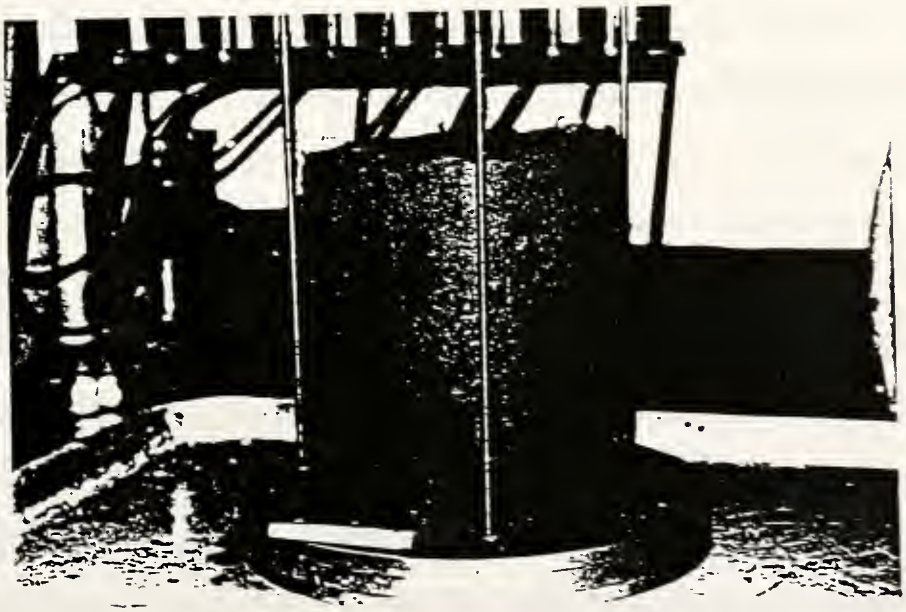


Figure 8.4 A sample of rubber-Crosby, photographed after the permeability testing

following relationship:

$$k = \frac{QL}{A(H_1 - H_2)} \tag{8.2}$$

Where,

k = coefficient of permeability, cm/sec

Q = average discharge, cm/sec

L = height of specimen, cm

A = cross-sectional area of specimen, cm^2

$(H_1 - H_2)$ = head difference, cm

The results from permeability testing of rubber-soils have been summarized in Table 8.1.

8.4 Studies on Permeability Testing of Chips

A laboratory study was conducted by Bressette (1984) to determine feasibility of using tire chips as an alternate to conventional aggregate in drainage layers/channels. He performed constant head permeability tests on compacted and uncompacted specimens of chopped scrap tire material (approximately 2-inch squares), shredded tires (100% passing 2-inch sieve), and coarse aggregate (open graded, percent passing sieves 2, 1.75, 1.50, and 0.50-in. was 100, 99, 43, 39, and 1%, respectively). The permeability values for the three materials were within the same order of magnitude, i.e., 10^4 ft/day (3.53 cm/sec), with only 3 exceptions in 42 tests. The range of permeability for uncompacted samples was reported from 4.9 to 59.3 cm/sec (1.38×10^4 to 16.8×10^4 ft/day) and for compacted samples the values varied from 2.89 to 21.98 cm/sec (0.82×10^4 t 6.23×10^4 ft/day). The results of their study have been summarized in Table 8.2. All values are in the upper range of permeability values required for subdrainage material.

Blumenthal and Zelibor (1992) reported a study, performed by Shive-Hattery Engineers & Architects, Incorporated (1990) for the Iowa Department of Natural Resources, which investigated the hydraulic properties of shredded scrap tires as a drainage soil substitute. They found that the average coefficients of permeability of 1.5 in. and 0.75 in. scrap tire chips were 2.07 and 1.93 cm/sec, respectively. Their results indicate that the size of tire chips does not significantly effect the coefficient of permeability.

8.5 Discussion

The values of coefficient of permeability for rubber-soils summarized in Table 8.1 appear very consistent and reasonable, based on a comparison of typical values for different soils and aggregates reported in the literature (see Table 8.2; Figure 8.5; Bressette, 1984; Freeze and Cherry, 1979; Hunt, 1986; and Lambe and Whitman, 1969). A critical analysis of results show that compactive effort and

Table 8.1 Summary of results from permeability testing of Rubber-Soils

Test No.	Testing Material/ Method of Sample Preparation	Dry Density (pcf)	Height of Sample (cm)	Head Difference (cm)	Hydraulic Gradient (cm)	Q (Average) (cm^3/sec)	Hydraulic Conductivity K (cm/sec)
1	One in. size chips/ impact compaction using standard proctor energy	40.58	22.86	38.26	1.674	293.45	0.558
2	One in. size chips/ impact compaction using standard proctor energy	40.35	22.86	36.10	1.579	280.27	0.565
3	One in. size chips/ impact compaction using 50% of standard proctor energy	39.67	22.86	33.00	1.444	294.42	0.649
4	One in. size chips/ impact compaction using modified proctor energy	42.38	22.86	33.00	1.444	243.15	0.536
5	Ottawa sand, no chips/ vibration under 2 psi for 8 min.	118.13	13.97	61.75	4.420	0.228	1.642x10^{-4}
6	Sand + 15.48% 1-inch chips/vibration	104.79	13.97	42.25	3.024	1.736	1.827x10^{3}
7	Sand + 30.07% 1-inch chips/vibration	95.53	13.97	42.75	3.060	3.354	3.489x10^{3}
8	Sand + 37.72% 1-inch chips/vibration	88.08	15.24	42.75	2.805	7.663	8.696x10^{3}
9	Crosby till, no chips/standard	118.91	15.24	134.75	8.842	2.462x10^{3}	8.863x10^{7}
10	Crosby till + 14.83% 1-inch chips/standard	106.37	15.24	135.00	8.858	4.914x10^{3}	1.766x10^{5}
11	Crosby till + 30.08% 1-inch chips/standard	86.67	15.88	61.65	3.882	2.581	2.116x10^{3}
12	Crosby till + 40% 1-inch chips/standard	74.84	22.86	60.20	1.826	7.300	8.824x10^{3}
13	Crosby till + 40% 1/2-inch chips/standard	74.42	22.86	41.75	1.826	5.58	9.727x10^{3}

Table 8.2 Summary of permeability test results (from Bressette, 1984)

Sample Description	Test #	Flow Rate (cu ft/sec)	Unit Weight (lb/cu ft)	Range of Permeabilities ($x10^4$ ft/day)
2" Shredded, Compacted	1	.089-.097	38.56	1.45 to 3.09
	2	.083-.089	38.04	0.82 to 2.63
	3	.085-.089	37.19	1.15 to 1.45
2" Shredded, Loose	1	-	-	-
	2	.081-.084	29.31	2.14 to 6.66
	3	.087-.095	29.22	1.49 to 3.61
2" Square, Compacted	1	.082-.096	37.29	1.08 to 1.16
	2	.094-.099	38.43	1.81 to 5.03
	3	.034-.101	38.40	2.95 to 6.23
2" Square, Loose	1	.091-.102	28.89	1.87 to 3.62
	2	.089-.095	29.80	1.38 to 16.8
	3	.088-.093	29.38	3.48 to 4.75
Class 3 Aggregate	1	.089-.093	107.52	1.50 to 3.00
	2	.087-.098	104.74	1.57 to 3.11
	3	.085-.092	105.33	2.78 to 16.0

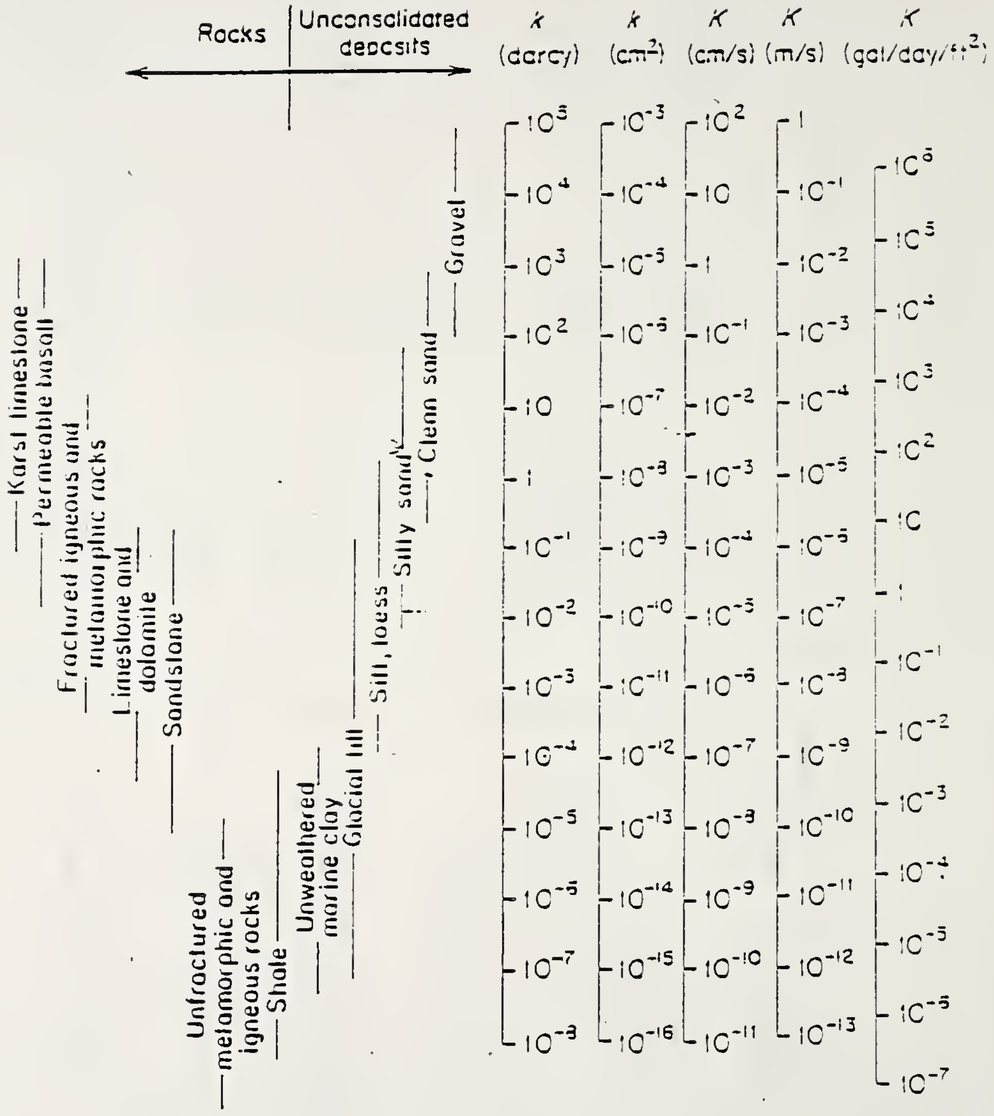


Figure 8.5 Range of permeability for soils and rocks (from Freeze and Cherry, 1979)

chip size do not appreciably effect the permeability of rubber-soils. However, a trend of increasing k with decreasing compactive energy and decreasing chip sizes is observed. The chip/mix ratio is the main factor which substantially influences the permeability, its value increases with increasing chip/mix ratios.

Compacted tire chips (2.0 to 0.75 in. nominal size) have permeability values equivalent to typical values for coarse gravel (see Tables 8.1 and 8.2; Blumenthal and Zelibor, 1992; and Freeze and Cherry, 1979). This property of chips renders them suitable for use in subdrainage as an alternate aggregate, if feasible from an environmental view point. Since they are a highly permeable material, pore pressure developments are minimized in tire fills and backfills. Use of tire chips in alternating layers with fine grained soils, like clays, silty clays, etc., will provide a shorter drainage path and thus help accelerate consolidation of the soil layers.

A large quantity of permeable aggregate is used by the highway industry annually. According to one estimate (Bressette, 1984), a significant portion of this material is used in drainage systems of highway pavements, where aggregate is not required to possess high structural properties. In this application, aggregate is required to possess good drainage characteristics, satisfactory filtering capabilities, high durability, safety against possibility of leaching undesirable materials into drainage water, etc. The use of filter fabric around the drainage layer can fulfill the filtering needs of a drainage system. Hence, even those permeable materials which may not satisfy the filtering criterion, can be considered for use in the drainage system in conjunction with filter fabric, if they fulfill other criteria.

The use of tire chips, which are generally of uniform gradation and, therefore, do not possess good filtering capabilities, can be considered for use in drainage layers in conjunction with filter fabric to replace conventional mineral aggregate. Tire chips are highly durable - they are practically non-biodegradable. However, certain research studies (e.g., MFCA, 1990) recommend that tire chips not be used in saturated zones of subgrades, since they may leach undesirable substances under adverse environmental conditions. Therefore, the use of tire chips in drainage layers may be deferred until their long term impact on environment is fully ascertained.

In a related application, shredded tires may be used as a permeable material in landfills. The design of new landfills encompasses the construction of single and double liners, with elaborate and reliable leachate collection systems, to satisfy the tough environmental regulations. In addition, more daily cover is being added to control odor, birds, and blowing trash. These factors contribute to a much higher landfill density and a greater requirement of mineral aggregate.

Permeable aggregate is required for the drainage layers in leachate collection system of a new landfill and in temporary/final cover of an old landfill. In this application, permeable material systems require high permeability under loading conditions. In addition, the material should be durable to prevent damage to the system due to freeze/thaw and wet/dry cycles. Shredded tires exhibit attractive engineering properties, which favor their use in this application, including: high physical and chemical durability - tires are practically non-destructible; intrinsically high tensile strength; lighter in weight; and permeability values comparable to conventional aggregates used in subdrainage layers (see Tables 7.1 and 7.2). Comparatively, the use of shredded tires in landfill leachate collection system is more promising, since leachates from tire material is not a matter of concern in this application.

8.6 Summary and Conclusions

Permeability tests have been conducted on tire chips, alone and also mixed with soils, using a large size custom-made constant head permeameter. The tests were performed according to procedures described in ASTM D-2437. The coefficient of permeability was computed using Equation (8.2). The results of permeability testing and the related information are summarized in Table 8.1.

The results indicate that the coefficient of permeability for 1-inch size tire chips varies from 0.54 cm/sec to 0.65 cm/sec with compactive effort decreasing from the equivalent of modified Proctor to 50% of standard Proctor. The permeability testing of rubber-soils demonstrate that the coefficient of permeability increases with increase in chip/soil ratios. The permeability of rubber-sand increases from $1.642\text{X}10^{-4}$ cm/sec for sand with no chips to $8.696\text{x}10^{-3}$ cm/sec for sand with 37.7% chips by weight of mix. However, the rate of increase in permeability values is higher for rubber-Crosby mix than rubber-sand with increasing chip/mix ratios. The values of k increase from $8.863\text{x}10^{-7}$ cm/sec to $8.824\text{x}10^{-3}$ cm/sec for 40% 1-chips by dry weight of mix for rubber-Crosby. This is an increase of about three order of magnitude, compared to only one order of magnitude increase in k for rubber-sand for similar increase in rubber/mix ratios.

The values of permeability are equivalent to the typical permeability values for coarse mineral aggregate. These high values of permeability render rubber-soils a useful fill material in embankment. The tire chips show a great promise for use in the drainage layers in leachate collection system of a new landfill and in temporary/final covers of an old landfill. Although, the use of tire chips in the drainage system of highway pavements show significant promise based on the its inherent attractive engineering properties, like durability, high permeability, low bulk density, availability at low or no cost, etc., its use in this application is not recommended at this point in time due to apprehensions about the long term impact of leachates from tire materials on the environment.

The use of shredded tires in the drainage layers of landfill leachate collection system and temporary/final landfill cover is considered feasible. However, there may be some apprehension about using this material in landfill cover, until the long term impact of using tire chips is determined. The use of shredded tires in landfill leachate collection system is very promising and should be promoted. The use of shredded tires as a lightweight permeable material in landfills would decrease the demand for mineral aggregate, improve our capability to design modern landfills on compressible clays, increase waste capacity of landfills, and would provide a means of disposal for used tires, which will have a very positive impact on the environment. In addition, the leachates from tire material will not be a matter of concern in this application of shredded tires.

CHAPTER 9

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 Background

When road embankments are constructed across deposits of weak, highly compressible soils both bearing capacity and settlement problems may be solved by using lightweight fill materials. Traditionally, waste from the timber industry, like sawdust and bark, slags and ashes from the power industry, or proprietary materials, such as expanded shale or Elastizell, have been used for lightweight embankment fill as replacement for conventional materials. Each of these materials suffers from some inherent drawbacks which make it less attractive for lightweight fill in highway structures (see Table 3.1 for properties of conventional lightweight materials). The highway industry is constantly endeavoring to develop a material which is lighter in weight, possesses higher durability, is environmentally acceptable, and is cost effective.

Certain field and laboratory studies indicated that these apparently contradictory requirements can be potentially reconciled by using rubber-soils as lightweight fill in embankments. Rubber-soil is defined as a blend of rubber chips obtained from shredding of scrap tires and various locally available soils mixed in various proportions for use as lightweight fill. The attractive characteristics of tire chips include: low bulk density; high durability, tire chips are practically non-biodegradable; available in abundance at relatively low cost or even free; and their use has very positive impact on the environment.

Scrap tires by the millions are discarded annually in the United States and other developed countries of the world, the bulk of which is currently landfilled or stockpiled. This consumes valuable landfill space, creates a fire hazard, and provides a prolific breeding ground for mosquitos. Efforts to sharply reduce the environmentally and economically costly practice of landfilling have stimulated the pursuit of non-landfill disposal or reuse of waste tires. Several beneficial uses for tires have been proposed in the past and some have been put into practice in various highway and non-highway applications. The use of tire chips as lightweight fill can sharply reduce the tire disposal problem, if they are found technically feasible, environmentally acceptable, and economically beneficial.

9.2 Summary

This study, based on comprehensive laboratory testing and evaluations, assesses the feasibility of using shredded tires in highway embankments as a lightweight fill. The study primarily focuses on determining compaction characteristics, stress-strain-strength behavior and hydraulic properties of compacted rubber-soils. In addition, the study briefly analyzes the environmental impacts of this application of waste tires. The findings of this study provide compressibility and strength parameters for design of embankments incorporating tire chips and for their post-construction performance prediction/evaluations.

A comprehensive work plan was developed to accomplish the research objectives set forth in Chapter 1. Two types of soils, one each from the fine and the coarse grained family of soils, were selected and prepared for testing purposes: 1) Ottawa sand - classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) and A-3(0) as per AASHTO; and 2) Crosby till - classified as sandy silty clay (CL-ML) as per USCS and A-4(0) according to AASHTO. Shredded tire samples of different sizes and gradations were procured from various tire processing agencies. A 6-inch diameter triaxial cell, a 12-inch diameter compaction/compression mold, an 8-inch diameter constant head permeameter, and related accessaries were designed and custom-made/modified for static and dynamic testing of compacted rubber-soils specimens to determine stress-strain-strength behavior and hydraulic characteristics of rubber-soil mixes. The MTS soil testing system, with loading frame suitably modified to accommodate large size compressibility and shear apparatus, was used to simulate static and dynamic field loading conditions. Necessary modifications were made in the hardware and software of the MTS System to impose the required loading conditions and acquire the data automatically during the testing.

The test data were analyzed and are presented in the form of tables/plots. Correlations are developed for use in design and performance evaluations of embankments containing tire chips. The thesis is structured as follows: Chapter 1 gives a brief description of the problem, lists the principal research objectives, gives the research approach to accomplish the stated objectives, and also presents an outline of the thesis; Chapter 2 gives background to the problem, presents an overview of current practice in recycling, reuse, and disposal alternatives and also contains a discussion on the various options available to reduce the tire disposal problem; Chapter 3 briefly describes the various lightweight materials traditionally used in highway construction, gives characteristics of tires, and summarizes the various field and laboratory studies on the use of shredded tires as lightweight fill; Chapter 4 describes the test materials and testing equipment/procedures, presents and analyzes the results from compaction of rubber-soils and tire chips alone; Chapter 5 contains the data and analysis from compressibility testing; Chapter 6 presents and analyzes the results from shear testing of rubber-soils under static loading conditions; and Chapter 7 contains the resilient modulus testing results and salient conclusions. Finally, hydraulic characteristics of laboratory prepared rubber-soil specimens are discussed in Chapter 8. The conclusions and recommendations of this study are presented in the subsequent subsections.

9.3 Current Practice

Chapters 2 and 3 present an overview of current practice in recycling, reuse, disposal options for scrap tires and a synthesis of information on the use of lightweight fill materials in highway construction. The tentative conclusions, based on a critical analysis of available information on rubber-soils from that reported in the literature, are as follow:

- The various options available to reduce the scrap tire disposal problem include: the reduction of waste tire generation; reuse of chemically unaltered material, in whole tires or after processing; the reclaiming of rubber, constituent materials, or chemicals from scrap tires to recycle them in the manufacture of new products; and the recovery of heat value. Of all the options currently available for the disposal of scrap tires, no single option appears to be so outstanding as to singularly significantly minimize the tire disposal problem, economically and also in an environmentally acceptable manner. Many options/processes need to be simultaneously tested and developed to solve the problem.

- Waste tires should be recognized as a valuable raw material. The factors which favor recycling and must be exploited, include: high physical and chemical durability, elastic in nature, intrinsically high tensile strength, lighter in weight, high calorific value, low costs, and positive impact of recycling on the environment. Factors which are impediments to recycling and must be considered while exploring/trying various recycling processes, include: inherently complex chemical composition and manufacturing process, which makes them bulky, resilient, practically non destructible, potentially combustible, and difficult to separate into ingredients; variability within the same type and also within different categories of tires; and questionable leachates under adverse environmental conditions.

- Of the available options in source reduction (i.e., longer service life, reuse, and retreading), reuse and retreading are economically/commercially viable and environmentally desirable options. Reduction in scrap tire generation can be encouraged by various measures, including regulatory requirements and economic incentives.
- Burying of whole tires is an environmentally undesirable option and a waste of valuable resources, and should be discouraged either by law or by high disposal fees.
- Scrap tires which cannot be recycled currently may be processed (cut, sliced, or shredded) and stored in monofills or installations in such a manner that they have no adverse impacts on environments, until development of technology in the future that may convert scrap tires into a high value product.
- The present technologies to reclaim rubber or separate tires into ingredients do not yield products that can compete, in terms of price or quality, with the similar products in the market.
- The potential areas for recycling tires in highways are: use of whole tires and tire sidewalls for soil reinforcement, soil retaining, sound and crash barriers, and erosion control; shredded tires as lightweight fill, in drainage layers to replace

coarse aggregate, and mulch for landscaping; and crumb rubber additive (CRA) in asphalt pavements (see Figure 2.2).

- Three highway applications which hold significant potential for future projection are: 1) use of shredded tires as lightweight fill; 2) use of crumb rubber in asphalt pavements; and 3) use of tires and its products for soil reinforcement.
- Non-highway applications which can potentially consume large quantities of waste tires are: breakwaters, artificial reefs, and reclaiming of rubber/other ingredients. A review of available technologies and markets suggest that these applications are not commercially beneficial at this point in time.
- Field studies indicate 10 to 15% settlement of tire shred embankments under 4 to 6 ft. of soil/pavement overburden pressure and average traffic conditions.
- The compacted field density of tire chips vary from 20 to 50 pcf depending on the size of the chips, method of compaction, and thickness of layers. A back hoe is found appropriate for spreading the tire chips. A D-8 crawler tractor is considered suitable for effective compaction.

9.4 Compaction Behavior

During this phase of the research, the testing program was formulated to develop quantitative information about the compaction characteristics of rubber soils and chips alone. The variables considered included: compaction methods, compactive efforts, tire chip sizes, chip/soil ratios, and size of compaction mold. The compaction tests were conducted following methods described in ASTM specifications D 698 (AASHTO: T99-61), D 1557 (AASHTO: T180-61) and D4253. Three different compactive efforts were used, i.e., impact energy equivalent to modified Proctor, standard Proctor, and 50% of standard Proctor method. Tire chips of seven different sizes ranging from sieve No. 4 to 2 inches have been investigated. The soil/chip ratios were varied from pure soil to pure chips (i.e., quantity of rubber chips was varied from 0 to 100% of dry weight of mix).

The following conclusions are drawn, based on a critical analyses of the results obtained from the compaction testing of rubber chips alone and rubber-soils.

- Vibratory methods of compaction are suitable for rubber-sand. Non-vibratory methods (e.g., Proctor type compaction) are more appropriate for compacting mixes of chips and fine grained soils.
- Although, a mold six times the maximum size of chips is considered adequate for conducting

compaction tests on rubber-soils, it has been found that the size of the mold effects the maximum density of rubber-soils. The small size molds (4 to 6 in.) may yield densities which may be about 10 to 15% lower than those obtained with larger molds (8 to 12 in.) for the same size of chips.

- The effect of compactive effort on the resulting density of rubber-soils decreases with increasing chip/soil ratios. Only a small effect is observed for an amount of chips greater than 20% of dry weight of mix. Similarly, the density of chips alone is also not much affected by the compactive effort. Only a modest compactive effort is required to achieve the maximum density of chips. This density is about one third that of conventional soil fills.
- Density of rubber-soils decreases with increasing chip/soil ratios and the relationship between density versus percent chips is almost linear. Correlations are developed (see Equations 4.2, 4.3, and 4.4) which can help in predicting the density of rubber-soils for geomaterials similar to the ones used in this research.
- The chip density is not very sensitive to the size of chips. However, a trend of increasing density with increasing chip size is found, except in the

case of the vibratory compaction method. In this case the maximum density decreases with increasing chip sizes.

9.5 Compressibility

Compressibility tests were conducted on tire chips, alone and also mixed with soils, to determine the load-deformation behavior of rubber-soils. A 12-inch diameter compressibility mold was designed and built for testing large size tire chips. The variables considered included: type of soils - Ottawa sand and Crosby till; methods of sample preparation - vibratory and impact compaction; compactive efforts - equivalent to modified, standard, 50% of standard, and no compaction; and chip sizes - varying from 0.50 to 2-inch. The samples were subjected to 3 or 4 load/unload cycles to determine the behavior of rubber-soils under repeated loads.

The data obtained were plotted as vertical strain versus logarithm of vertical stress in Chapter 5. Based on a critical analysis of the compressibility test results, the following observations are made:

- The load-deformation response of tire chips indicates that three mechanisms are mainly responsible for total compression of tire chip samples: a) compression due to rearrangement/

sliding of chips - a small compression occurs due to this, mainly during the first loading cycle and is mostly irrecoverable; b) compression due to bending/flattening of chips - responsible for the major portion of total compression and is mostly recoverable on unloading; and c) compression due to elastic deformation of tire chips - a very small compression occurs due to this mechanism mainly at high stresses (≈ 20 psi or higher) and all of it is recoverable. This indicates that compression of rubber chips can be reduced by increasing confining/overburden pressures or filling air voids with material less compressible than tire chips.

- The variation in chip sizes had little effect on load-deformation response for higher compactive efforts, i.e., equivalent to modified and standard Proctor tests. However, a trend of higher vertical strains were observed in the case of 0.5-inch chips, compacted using 50% of standard compactive effort.
- The increase in compactive effort from standard to modified had no effect on the compression curves for various chip sizes. However, samples compacted using 50% of standard Proctor effort yielded vertical strains 2% to 4% higher during the first loading cycle than those compacted with standard or

modified effort. The uncompacted samples also produced higher strains during the first loading cycle. However, compactive effort had little effect on the load-deformation response of chips during subsequent load/unload cycles.

- The curves from rubber-soils with varying chip/mix ratios show that the total compression of samples increases with increasing percent of tire chips, the highest value of compression being for 100% chips. This demonstrates that a blend of rubber-soil provides a mix with lower void ratio, which compresses less than one of pure chips, and will also cause lesser settlement of foundation soil due to reduced weight of fill. About 38% chips by weight of mix is an optimum value for the quantity of chips in a rubber-soil mix, where large settlements are a matter of concern. This chip/soil ratio will yield a compacted dry unit weight of rubber-soil mix which is about two thirds that of soil alone.
- A comparison of vertical strains at different stress levels and compressibility parameters for three materials, i.e., chips, rubber-sand, rubber Crosby, suggests that rubber-sand is a very promising lightweight geomaterial, the use of which should be promoted in fills near bridge abutments,

and other highway structures where settlements are to be kept to the minimum.

- A summary of compressibility parameters (CR, RR, and SR) are presented in Chapter 5 for tire chips, rubber-sand and rubber-Crosby. These parameters can be used as guides for design and evaluation of embankments incorporating rubber-soils.

9.6 Shear Behavior

A number of triaxial compression tests were performed on rubber-soils for determining the feasibility of using tire chips in highway embankments as lightweight geomaterials. Tire chips of different sizes and gradations and two types of soils were tested in the laboratory using a 6-inch diameter triaxial apparatus. The variables considered included: type of soils, methods of sample preparation, size of chips, ratios of tire chips/mix, and confining pressures.

The following salient conclusions are drawn concerning shear behavior of rubber-soils based on a critical evaluation of the test results:

- Unlike soils, the samples of tire chips do not fail by yielding or have a single shear plane, instead the samples exhibit a strain hardening behavior and continuously become stiffer with increased axial straining. The chip specimens at low confining pressures demonstrate symmetrical bulging. The specimens sheared at high confining pressures compress vertically, with little lateral spreading, and continue to become stiffer even at large strains, when the capacity of the apparatus is reached. Confining pressure is the most important factor effecting the strength of chips. Size of chips and compactive efforts do not significantly effect the shear behavior of tire chips. However, a trend of increasing deviatoric stresses with increase in chip sizes and compactive effort is observed.

- The shear behavior of rubber-sand is mainly affected by the level of confining pressures and chip/mix ratios. Higher confining pressures yield higher strength values. The rubber-sand samples exhibit behavior similar to that of sand alone at low chip/soil ratios and similar to that of chips alone at high chip/soil ratios. Compactive effort and chip size has little effect on shear behavior of rubber-sand. Tire chips have a reinforcing effect on rubber-sand mixes. The increase in strength is a maximum at a chip/soil ratio of about 39% at low to medium confining pressures (≈ 4 to 20 psi), which is considered an optimum ratio for rubber-sands for use as lightweight geomaterials.

- Similar to rubber-sands, the rubber-Crosby mixes exhibit stress-strain behavior similar to Crosby till at low chip/mix ratios and like chips alone at higher chip/soil ratios (>20% chips by the dry weight of mix). Unlike rubber-sand, tire chips do not have an appreciable reinforcing effect on the behavior of Crosby till. The inclusion of tire chips in Crosby till reduces the deviatoric stress values compared to those of soil alone at corresponding strain levels and increases the strain at failure. The compactive effort and size of chips do not significantly effect the stress-strain behavior of rubber-Crosby.
- The failure criterion for rubber-soils needs to be based on allowable strains instead of peak or yielding strength. Strength parameters for rubber-soils for 5, 10, 15, and 20% strain levels have been determined and summarized in Tables 6.4 to 6 for tire chips, rubber-sand, and rubber-Crosby, respectively.

9.7 Resilient Modulus Testing

A laboratory testing program has been conducted on tire chips of variable sizes and two test soils to determine the resilient characteristics of rubber-soils. The chip and rubber-Crosby samples were prepared using impact, Proctor type compaction and the rubber-sand samples by vibratory method of compaction. The resilient modulus tests were performed on rubber-soil samples with chip/mix ratios varying from 0 to 100%. The following salient conclusions are drawn concerning resilient modulus of rubber-soils:

- The resilient modulus of soils decreases with increase in chip/mix ratios. This reduction in modulus is stress dependent and is substantial, up to 80% or even greater depending on the chip/mix ratios and the state of stress. The reduction in modulus is greater for rubber-Crosby than rubber-sand.
- The resilient modulus data from rubber-soils show a significant scatter, greater than that observed for conventional soils.
- Chip size has no effect on the resilient characteristics of rubber-soils.
- The values of resilient modulus for rubber-soils improve under increased confining pressures. This implies that the use of properly confined rubber-soil fill as lightweight geomaterial is viable. A 3-ft. layer of soil/aggregate as an overburden pressure is considered adequate.
- The resilient modulus tests on rubber-soils yield reasonable values for the regression constants of Equation 7.2. The B constant for rubber-sand does

not vary much with variation in chip/mix ratios and has a mean value of 0.91±0.12. A correlation has been found between chip/mix ratios, in percent, and constant A (see Equation 7.3). This regression equation (r^2=0.92) can be used to predict the variation in constant A due to addition of tire chips in the sand. If the value of resilient modulus for soils with no chips is known, the values of resilient modulus for rubber-sand with chip/mix ratios of up to 40% can be estimated. The regression constants of Equation 7.2 can also be determined experimentally for accurate estimates of resilient modulus values for rubber-soils.

9.8 Permeability

Permeability tests have been conducted on tire chips, alone and also mixed with soils, using a large size custom-made constant head permeameter. The tests were performed according to procedures described in ASTM D-2437. The coefficient of permeability was computed using Equation 8.2. The results of permeability testing and the related information are summarized in Table 8.1.

- The results indicate that the coefficient of permeability for 1-inch size tire chips varies from 0.54 cm/sec to 0.65 cm/sec with compactive effort decreasing from the equivalent of modified Proctor to 50% of standard Proctor.

- The permeability testing of rubber-soils demonstrate that the coefficient of permeability increases with increase in chip/soil ratios. The permeability of rubber-sand increases from $1.642x10^{-4}$ cm/sec for sand with no chips to $8.696x10^{-3}$ cm/sec for sand with 37.7% chips by weight of mix. However, the rate of increase in permeability values is higher for rubber-Crosby mixes than for rubber-sand with increasing chip/mix ratios. The values of k increase from $8.863x10^{-7}$ cm/sec for Crosby till with no chips to $8.824x10^{-3}$ cm/sec for 40% 1-inch chips by dry weight of mix. This is an increase of about four order of magnitude, compared to only one orders of magnitude increase in k for rubber-sand for similar increase in rubber/mix ratios.
- The values of permeability for tire chips are equivalent to the typical values for coarse mineral aggregate. These high values of permeability render tire chips a useful fill material in embankments and in drainage layers of leachate collection systems of landfill, temporary/final covers of an old landfill, and in drainage layers of pavement systems. However, the use of tire

chips in drainage layers of landfill cover and pavements may be deferred until the long-term impacts of leachates from tires is known.

9.9 Economic Implications

The cost of using shredded tires in embankments depend on a number of factors that vary with the local conditions, including: cost of chips (primary shreds are generally available free at the source in most of the states at this point in time); distance of shredding facilities from the site and the cost of transportation; cost of placement and compaction; incentives offered by the state in the form of subsidies/rebates, etc.; and the cost of conventional mineral/lightweight aggregates. In Indiana, the major vendor of shredded tire materials is located in East Chicago. Currently, they are willing to provide primary tire shreds without cost. Transportation costs in Indiana vary from $5 to $10/ton for a distance of 100 miles. The exact economic benefits can be determined on a case-by-case basis.

9.10 Recommendations

9.10.1 A Solution to the Scrap Tire Problem

It is evident that the waste tire problem in the United States is of great magnitude and has far reaching environmental and economic implications. It is found, based on a critical analysis of the available options for reuse, recycling, and disposal of scrap tires, that no single option can solve this problem. A comprehensive strategy needs to be developed and pursued to combat this problem at government, industry, and public levels. Federal, state and local officials need to integrate their efforts to muster support of the people to solve this problem. A five point approach, to be adopted at national and state level, is recommended:

1) Develop and implement comprehensive laws governing manufacture, discards, disposal, storage, incineration, reuse, and recycling of tires.
2) Implement measures to reduce the number of scrap tires generated (see Chapter 2 for details).
3) Promote use of scrap tires and their products in highway and non-highway applications which hold great promise for consuming large quantities of tires in an environmentally acceptable manner, with significant economic benefits (see Subsection 9.3).
4) Permit storage of processed tires (i.e., shredded, sliced, or chopped) which cannot be recycled currently, in safe installations/monofills where they have no adverse environmental impacts, for use in the future when technological advances can convert processed tires into high value products.
5) Allow incineration of tires only in those tire-to-energy facilities which can burn tires or tdf efficiently, while complying with all the emission

control regulations.

9.10.2 Use of Tires as Lightweight Geomaterials

The engineering properties of rubber-soils determined as part of this research, namely: index properties, compactibility, compressibility, shear strength, resilient modulus, and permeability, suggest that rubber-soils show significant promise for use in highway embankments. It is found that the use of shredded tires in highway construction offers technical, economic, and environmental benefits under certain conditions. The salient benefits of using tire chips are: reduced weight of fill - helps increase stability, reduce settlements, and correct or prevent slides on slopes; serve as a good drainage medium, thus preventing development of pore pressures during loading of fills; reduce backfill pressures on retaining structures; provide separation to prevent underlying weak/problem soils from mixing with subgrade/base materials; allow conservation of energy and natural resources; and can consume large quantities of local waste tires, which has a very positive impact on the environments.

There are some potential problems associated with the use of shredded tires in highway embankments, which include: long term impacts of leachates from tires on environments; fire risk; and large compressibility of tire chips. A recent field study reports that shredded tires show no likelihood of having adverse effects on groundwater quality (Bosscher, et al., 1992). However, long term concerns under adverse environmental conditions still persist. Proper soil cover is required on top and side slopes of shredded tire embankments for safety against fire. During construction, normal caution is required to be observed against fire in stockpiled tires or in embankment tires that have not yet been capped with soil. Potentially large settlements can be reduced by providing a thicker soil cap and using a rubber-soil mix instead of chips alone. Detrimental effects of post-construction settlements can be reduced by using tires under flexible pavements only and letting the chips settle under traffic for some time before laying a final surface course.

Rubber-soils with chip/mix ratios of 38% (subsequently referred to as the optimum ratio) or less may be used in embankments where large settlements are unacceptable, like near bridge abutments, etc. Rubber-sand at optimum chip/mix ratio possesses excellent engineering properties, including: easy to compact and yield low dry density; low compressibility; high strength; and excellent drainage characteristics. The free draining characteristics of rubber-sand also reduces the possibility of undesirable leachates from tires, since water does not stagnate in fills. The availability of tire chips in abundance and almost free at the source, and the positive impact of using large quantities of tires are added benefits of using rubber-sand in highway embankments. In summary use of tire chips and rubber-sand offer very promising technical, environmental, and economic benefits and their use in highway embankments, above groundwater table, should be promoted.

The use of rubber-Crosby mixes in embankments offer some technical benefits, like low dry density - the density of mix at 40% chip/mix ratio is about two thirds that of conventional fill, and good hydraulic characteristics - addition of chips by about 40% dry weight of mix increases the coefficient of permeability by four order of magnitude. However, this material has high compressibility, low shear strength, and is difficult to mix/compact in the field. The choice of using a mix of tire chips and fine grained soils is recommended to be made on a case-by-case basis, depending upon the site conditions, type and availability of borrow material, and desired engineering characteristics of fill material, like strength, compressibility, density, permeability, etc.

It is recommended, based on significantly lower values of resilient modulus of rubber-soils compared to conventional subgrade soils, that tire chips alone and also mixed with soils, should not be used in the subgrade portion of highway pavements. Rubber-soils are recommended to be used in embankments and not within three ft. of asphalt pavement surface, to avoid subjecting asphalt pavements to fatigue stresses, which may cause larger deflection of the pavement surface under repeated traffic loads and thus affect the service life of the pavement.

9.10.3 Further Research on Rubber-Soils

A comprehensive laboratory study is recommended to assess the feasibility of using rubber-soils in loaded and unloaded backfills and in slope stabilization situations. The study should also consider the reinforced soil applications of tire chips and rubber-soils in combination with geogrids and geotextiles. The study should include: determination of the coefficient of lateral pressure for rubber-soil fills; measurement of compressibility and strength parameters of chips and rubber-soils mixes under saturated conditions; values of interface friction between geogrids/geotextiles and rubber-soils; hydraulic characteristics of rubber-soils under variable confining pressures; and computer simulations for the use of tire shreds as a loaded or unloaded backfill. Finally, computer simulations of the improvement in slope stability achieved in reinforced soil applications of rubber-soils and in embankments on soft ground is also recommended.

A field study which should include the construction of a test embankment, with adequate monitoring devices, to measure compressibility and leachates from fill is also recommended. The embankment should preferably have three section: 1) containing tire chips alone; 2) rubber-sand mix; and 3) chips mixed with locally available fine grained soil. The study will be very helpful in determining long-term performance and development of correlations between laboratory and field parameters. The test embankment may be constructed according to the specifications recommended in the subsequent subsections.

9.10.4 Specifications for Embankments Containing Tire Chips

The specifications are developed for embankments incorporating tire chips, based on the past experience of various states who experimented with the use of tire chips as lightweight fill in embankments (e.g., Bosscher, et al., 1993; Edil et al., 1990; Lamb, 1993; Read, et al., 1991; and Whitmill, 1991) and the analysis of results obtained from this laboratory study. These specifications are intended to serve as guidelines for the INDOT, basically for the construction of embankment for field study. The suggested specifications may be further refined in the light of data obtained from the field study. The updated specifications may then be included in the Indiana Department of Highways, Standard Specifications (1988). Following are the specifications for embankments incorporating tire chips:

- The material be from waste tires, which are shredded into chips of appropriate size and gradation.
- The gradation of tire chips be such that: 80% of the material passes an 8-in. screen; at least 50% passes 4-in. screen; all pieces have at least one side wall severed from the face of the tires; and the largest allowable piece be 18 inch in length.
- All metal fragments be firmly attached and 98% embedded in the tire sections from which they were cut. No metal particles be placed in the fill without being contained within a rubber segment. Ends of the metal belts and beads are expected to be exposed only in the cut faces of some tire chips.
- During construction of embankments, tire chips may be compacted in 1.5 to 2-ft. thick layers. A back hoe is considered appropriate for spreading the material evenly. Three passes of D-8 crawler tractor are considered enough to compact the material to the desired density. The design density may be decided by either conducting standard Proctor compaction tests on tire chips of lower size, using compaction mold at least six times the maximum size of chips or using the tire

chip densities and co-relations developed as a result of this laboratory study by the author as a guideline (see Chapter 4). The density achieved in the field shall be greater than 95% of the maximum dry density of chips obtained in laboratory. Proctor type compaction of air dried chips is recommended to determine the design density.

- The tire chips be placed above the water table and out of contact with groundwater.
- The road surface be designed and built to provide for adequate surface drainage in order to avoid water seepage through the road surface and the tire material.
- A synthetic geotextile fabric shall be preferably placed above and below the shredded tire material to keep the material together and to prevent the surrounding materials from migrating into the lightweight fill.
- A 3-ft. thick low permeability compacted material shall be placed over the tire shreds, on top and sides of embankments, to prevent the intrusion of surface water, providing safety against fire, ensuring adequate confining pressure, reducing fatigue stresses in pavement surface course, and overcoming the detrimental effects of traffic loading on tire chips lightweight fill.

- The compressibility and strength parameters, summarized in Chapters 5 and 6, respectively, may be used for design and evaluation of embankments containing tire chips, until such time as more extensive testing results are available.
- Lysimeters may be installed to collect samples for analysis of leachates from tire chips to determine the effects of leachates on the environments/ groundwater quality.
- Appropriate monitoring devices, e.g., settlement plates, inclinometers, etc., may be placed in the embankments to determine their technical performance.
- Adequate precautions against fire be observed on site before and during construction
- Tire chips should not be used in areas or with fills of extreme pH values or of highly variable pH values, since tire chips under extreme pH conditions leach substance which may effect the groundwater quality.

9.10.5 Specifications for Embankments Containing Rubber-Sand

The specifications suggested for tire chips shall also apply to embankments incorporating rubber-sand, except that the preferable method of compaction for rubber-sand is vibratory instead of Proctor type. In addition the following specifications are suggested to serve as a guide for the INDOT:

- The materials selected shall be well graded medium or coarse sand and tire chips, having gradation suggested in Subsection 9.10.4.
- Sand should not have extreme pH values.
- The ratio of chips to dry weight of rubber-sand mix shall be 38% or less.
- Air dried chips shall be compacted in layers of 1 to 1.5 ft. thick, as per the procedures given in the preceding subsection, and then dry sand be poured over the chips such that the chip-sand ratio achieved is less than 38% chips by the weight of mix. The rubber-sand mix is then compacted dry to the design density, using vibratory equipment.
- The design density shall be selected either performing laboratory compaction tests on chip-sand mix or using a value obtained as a result of this laboratory study (see Chapter 4), if a similar material is used.
- The compressibility and shear strength parameters obtained for rubber-sand may be used for design and evaluation of embankments incorporating materials similar to that used in this study.

9.10.6 Specifications for Embankments Containing Mix of Tire chips and Fine Grained Soils

The choice of using a mix of tire chips and fine grained soils in embankments should be made on case-by-case basis as suggested and explained in Subsection 9.10.2. The specifications suggested in Subsection 9.10.4 for embankments containing tire chips shall also apply to embankments incorporating mixes of tire chips and fine grained soils (henceforth called rubber-soils). In addition, the following specifications are suggested:

- The ratio of chips to dry weight of rubber-soil mix shall be 38% or less.
- Air dried tire chips shall be spread evenly in layers of 9-in. to 1-ft. with the help of a back hoe and then soil, at optimum moisture content, be spread over the chips. Tire chips and soil shall be mixed together with a D-8 crawler tractor having prongs at the tail, as usually used for tilling fields.
- The minimum field density for rubber-soil shall be greater than 95% of the maximum dry density achieved by the standard Proctor compaction method. The design density and the optimum moisture content shall be determined by conducting compaction tests on rubber-soil in the laboratory using a compaction mold at least six times the maximum size of tire chips being tested in the laboratory or selecting

a value based on results of this study on rubber-Crosby mixes (see Chapter 4), if a similar material is used.

- It is re-emphasized that soil used must not be of extreme pH values and its pH value should remain stable, when water is added to the soil.

9.10.7 Screening Requirements for Tire Chips Used as Lightweight Geomaterial

The tire chips used for this research were obtained from different local tire shredding vendors. The chips had different gradations and their maximum sizes varied from 0.25 to 2-inch (see Figure 4.1). One of the objectives of this research was to assess the effect of variability in the type of tire chips and their gradation on the engineering properties of rubber-soils. It has been determined as a result of this research that gradation of tire chips with maximum sizes greater than 0.50-in. and the usual variability in shredded tires do not significantly effect the results of compaction, compressibility, shear, resilient modulus, and permeability testing. Therefore, primary shreds can be used in embankments as lightweight geomaterials. However, some limits are imposed in the specifications on the upper size of tire chips that can be used in rubber-soils as lightweight geomaterials, for convenience of compaction and handling during placement (see Subsection 9.10.4).

9.10.8 Testing Standards for Rubber-Soils

Rubber-soils are special geomaterials, with maximum particle sizes larger than that of typical subgrade soils. Therefore, rubber-soils mixes can not be tested in conventional geotechnical apparatus routinely used for soils. They require large size apparatus compatible with the large size tire chips. It is found that rubber-soil specimens six times the maximum size of tire chips being tested are appropriate for compaction, compressibility, shear, resilient modulus, and permeability testing of rubber-soils. The description of testing equipment, operating instructions, and testing procedures for determination of various engineering properties of rubber-soils are given in respective chapters of this report, and are recommended to be used by the INDOT for determining various engineering properties, namely: index, compaction, compressibility, shear, resilient modulus, and permeability of rubber-soils. The testing standards may finally be included in the testing manual of the INDOT.

LIST OF REFERENCES

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Notes:

ASCE = American Society of Civil Engineers

ASTM = American Society for Testing and Materials

DOT = Department of Transportation

ENR = Engineering New Record

FHWA = Federal Highway Administration

NAE = National Academy of Engineers

NAS = National Academy of Sciences

NCHRP = National Cooperative Highway Research Program

NRC = National Research Council

TRR = Transportation Research Record

TRB = Transportation Research Board

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Appendix A

Senate Bill No. 209

Introduced Version

SENATE BILL No. 209

Introduced by: Gard

__________, read first time and referred to Committee on

DIGEST OF INTRODUCED BILL

Citations Affected: None (noncode).

Synopsis: Recycled materials in road construction. Requires the Indiana department of transportation, in cooperation with the highway extension research project for Indiana and the Purdue University School of Engineering, to study the feasibility of using recycled asphalt, concrete, waste tires, and demolition materials in road construction. Requires the department to report the department's findings to the legislative council, the governor, and the general assembly.

Effective: Upon passage.

First Regular Session 107th General Assembly (1991)

A BILL FOR AN ACT concerning recycling.

Be it enacted by the General Assembly of the State of Indiana:

SECTION 1. (a) The Indiana department of transportation established by IC 8-23-2-1, in cooperation with the highway extension and research project for Indiana counties and cities and the Purdue University School of Engineering, shall study the feasibility of using recycled asphalt, concrete, waste tires, and demolition materials in road construction projects undertaken by the department or by the Indiana transportation finance authority established by IC 8-9.5-8-2.

(b) In conducting the study required by this SECTION, the Indiana department of transportation shall:

(1) consider the development of bid specifications to promote the use of; and

(2) analyze the costs, life cycle, and relative availability of;

recycled asphalt, concrete, waste tires, and demolition materials.

(c) The Indiana department of transportation shall prepare a report on the results of the department's study under this SECTION and submit that report to the legislative council, the governor, and the general assembly before July 1, 1992.

(d) This SECTION expires July 1, 1992.

SECTION 2. Because an emergency exists, this act takes effect upon passage.

Appendix B

House Enrolled Act No. 1056

HOUSE ENROLLED ACT No. 1056

AN ACT to amend the Indiana Code concerning the environment.

Be it enacted by the General Assembly of the State of Indiana:

SECTION 1. (a) The Indiana department of transportation established by IC 8-23-2-1, shall, on its own or in cooperation with a state supported college or university, study the feasibility of using recycled asphalt, concrete, coal combustion products, waste tires, and demolition materials in road construction projects undertaken by the department.

(b) In conducting the study required by this SECTION, the Indiana department of transportation shall:

  (1) consider the development of bid specifications to promote the use of; and
  (2) analyze the costs, life cycle, and relative availability of;

recycled asphalt, concrete, coal combustion products, waste tires, and demolition materials.

(c) The Indiana department of transportation shall prepare a report on the results of the department's study under this SECTION and submit that report to the

legislative council, the governor, and the general assembly before July 1, 1992.

(d) This SECTION expires July 1, 1992.

SECTION 2. IC 13-7-23-2.5 IS ADDED TO THE INDIANA CODE AS A NEW SECTION TO READ AS FOLLOWS: **Sec. 2.5. As used in this chapter, "person" means an individual, a corporation, a partnership, or an unincorporated association.**

SECTION 3. IC 13-7-23-3, AS AMENDED BY HEA 1406 OF THE 1991 REGULAR SESSION OF THE GENERAL ASSEMBLY, IS AMENDED TO READ AS FOLLOWS: Sec. 3. As used in this chapter, "tire" means a continuous solid or pneumatic rubber covering ~~encircling the~~ **that is designed to encircle a** wheel of a motor vehicle (as defined in IC 9-13-2-105(a)).

SECTION 4. IC 13-7-23-11, AS ADDED BY P.L.19-1990, SECTION 36, IS AMENDED TO READ AS FOLLOWS: Sec. 11. (a) The waste tire management fund is established for the purpose of assisting the department in the removal and disposal of waste tires from sites where the waste tires have been disposed of improperly.

(b) The expenses of administering the fund shall be paid from money in the fund.

(c) Money in the fund at the end of a state fiscal year does not revert to the state general fund.

(d) Sources of money for the fund are the following:

(1) Fees paid under section 8(a)(4) of this chapter **and IC 13-7-23.2-13(d).**

(2) Fees established by the general assembly for the purposes of this chapter.

(3) Appropriations made by the general assembly.

(4) Gifts and donations intended for deposit in the fund.

SECTION 5. IC 13-7-23.2 IS ADDED TO THE INDIANA CODE AS A NEW CHAPTER TO READ AS FOLLOWS:

Chapter 23.2. Disposition of Waste Tires

Sec. 1. As used in this chapter, "customer" means a person who purchases at least one (1) new tire from a retailer.

Sec. 2. As used in this chapter, "new tire" means a tire that has never been mounted on a wheel of a vehicle.

Sec. 3. As used in this chapter, "person" has the meaning set forth in IC 13-7-23-2.5.

Sec. 4. As used in this chapter, "retailer" means a person engaged in the business of selling new tires at

retail in Indiana.

Sec. 5. As used in this chapter, "tire" has the meaning set forth in IC 13-7-23-3.

Sec. 6. As used in this chapter, "vehicle" has the meaning set forth in IC 9-13-2-196.

Sec. 7. As used in this chapter, "waste tire" has the meaning set forth in IC 13-7-23-4.

Sec. 8. As used in this chapter, "waste tire transporter" means a person who engages in the business of accepting waste tires from retailers and transporting the waste tires to one (1) or more other locations.

Sec. 9. As used in this chapter, "wholesaler" means a person engaged in the business of selling new tires at wholesale in Indiana.

Sec. 10. (a) In each retail establishment in which a retailer sells new tires, the retailer shall post in a conspicuous place a written notice that bears the following statements:

> "Do not put waste tires in the trash."
> "Recycle your waste tires."
> "State law requires us to accept your waste tires for recycling or proper disposal if you purchase new tires from us."

(b) A notice required by this section must be at least eight and one-half (8.5) inches wide and eleven (11) inches high.

(c) A person who knowingly violates this section commits a Class C infraction.

Sec. 11. A retailer who sells new tires to a customer shall accept waste tires that the customer presents to the retailer at the place where possession of the new tires is transferred to the customer. The number of waste tires that a retailer is required to accept from a customer under this section is equal to the number of new tires that the retailer sells to the customer.

Sec. 12. (a) A retailer shall dispose of waste tires in the retailer's possession by one (1) or more of the following means:

(1) Delivery to a wholesaler or to an agent of a wholesaler.
(2) Delivery to a manufacturer of tires.
(3) Delivery to a facility that:
  (A) recycles tires; or
  (B) collects tires for delivery to a recycling facility.

(4) Delivery to a permitted final disposal facility regulated under IC 13-7.

(5) Delivery to a waste tire storage site (as defined in IC 13-7-23-5).

(6) Delivery to a facility operated as a waste tire cutting facility under a permit issued by the commissioner.

(7) Delivery to a registered waste tire transporter or a person who operates a municipal waste collection and transportation vehicle licensed under IC 13-7-31.

(b) A person referred to in subsection (a) is not required to accept waste tires from a retailer.

Sec. 13. (a) This section does not apply to a person who operates a municipal waste collection and transportation vehicle licensed under IC 13-7-31.

(b) A person may not act as a waste tire transporter unless the person is registered with the department as a waste tire transporter. A person who registers with the department as a waste tire transporter shall disclose the following:

(1) The person's name.

(2) The address of the person's principal office.

(3) The addresses of any offices maintained by the person in Indiana.

(c) The rules adopted under section 14 of this chapter must adopt a manifest form and require a waste tire transporter to prepare and carry a manifest based upon that form each time a waste tire transporter transports waste tires. The format and wording of the form must require a waste tire transporter to enter information in each manifest indicating the source and number of waste tires to be transported and the destination to which the waste tires are transported.

(d) Until the rules prescribing a manifest form are adopted under subsection (c), a waste tire transporter may use a manifest form designed by the waste tire transporter. A form designed and used under this subsection must meet the format and wording requirements set forth in subsection (c).

(e) A person who acts as a waste tire transporter in Indiana shall pay an annual registration fee of twenty-five dollars ($25).

(f) Within thirty (30) working days after a waste tire transporter transports a quantity of waste tires, the waste tire transporter shall transmit to the department one (1) copy of the manifest concerning the transportation of the quantity of waste tires.

(g) Each manifest copy received by the department under this section is a public record under IC 5-14-3 and shall be made available to the public for inspection and copying during normal office hours, unless the information in the manifest is determined to be confidential data under IC 13-7-16-3.

Sec. 14. The solid waste management board shall adopt rules under IC 4-22-2 and IC 13-7-7 to implement this chapter.

Sec. 15. This chapter expires January 1, 1994.

SECTION 6. (a) The following definitions apply throughout this SECTION:

(1) "Cutting" means to cut a waste tire into eight (8) or more parts.

(2) "Person" has the meaning set forth in IC 13-7-23-2.5.

(3) "Tire" has the meaning set forth in IC 13-7-23-3.

(4) "Tire piece" means one (1) of the parts into which a waste tire is separated through cutting.

(5) "Waste tire" has the meaning set forth in IC 13-7-23-4.

(6) "Waste tire cutting facility" means a facility at which waste tires are:

(A) stored above ground before cutting; and

(B) subjected to cutting, either by equipment permanently located at the site or mobile equipment operating temporarily at the site.

(b) A person may not operate a waste tire cutting facility unless the person holds a permit issued under this SECTION. To obtain a permit for the operation of a waste tire cutting facility, a person must do the following:

(1) Submit to the department of environmental management a description of the facility for which the permit is sought, including a description of:

(A) the location of the facility;

(B) the buildings on the site of the facility and equipment to be used on the site;

(C) the area within the facility that is to be used for the storage of tire pieces; and

(D) the maximum amount of cubic yards of tire pieces that the person will store at the facility.

(2) Submit a written, signed commitment to store tire pieces at the facility only in compliance with

subsection (g).

(c) A person that operates a waste tire cutting facility under this SECTION shall pay a fee of one hundred dollars ($100):

(1) upon being issued a permit under this SECTION; and

(2) once in each year that the permit is in effect, beginning one (1) year after the issuance of the permit.

The proceeds of this fee shall be deposited in the waste tire management fund established under IC 13-7-23-11.

(d) The commissioner may not issue a permit to a person under this SECTION unless the person has established an escrow account that would be available to the commissioner to pay the cost of removing the waste tires and tire pieces from the site of the person's facility if the person ceased operations at the facility and was unwilling, unable, or unavailable to remove the tires and tire pieces from the site, and removal was necessary to protect the environment. A person that operates a waste tire cutting facility under this SECTION shall deposit in the account four dollars and eighty cents ($4.80) per cubic yard of tire pieces stored at the facility until the amount of money in the account equals the maximum amount of cubic yards the person submitted under subsection (b)(1)(D) multiplied by four dollars and eighty cents ($4.80). When the amount of money in a person's account equals the maximum amount of cubic yards the person submitted under subsection (b)(1)(D) multiplied by four dollars and eighty cents ($4.80), the person may store waste tires at the person's facility without depositing additional money in the person's account if the amount of cubic yards of tire pieces stored at the facility does not exceed the maximum amount of cubic yards the person submitted under subsection (b)(1)(D).

(e) A person may not store more than the maximum amount of cubic yards of tire pieces submitted under subsection (b)(1)(D) at a waste tire cutting facility unless the person:

(1) obtains the commissioner's approval; and

(2) deposits an additional four dollars and eighty cents ($4.80) for each cubic yard of tire pieces stored at the facility that exceeds the maximum amount of cubic yards submitted under subsection (b)(1)(D).

(f) A person may receive a refund of all or part of the money the person has deposited in an escrow account established under subsection (d):

(1) before the person ceases operations at a waste tire cutting facility if:

(A) the person applies to the commissioner in writing;

(B) the amount of cubic yards of tire pieces stored at the facility multiplied by four dollars and eighty cents ($4.80) is less than the amount of money the person has deposited in the escrow account; and

(C) the commissioner approves the refund; and

(2) after the person ceases operations at a waste tire cutting facility if:

(A) the person applies to the commissioner in writing; and

(B) the commissioner determines that the money is not needed to remove waste tires and tire pieces from the site of the person's facility.

Interest that accrues on money deposited in an escrow account may not be refunded.

(g) At a waste tire cutting facility operated under this SECTION, tire pieces may be stored outdoors in banks. However, the storage of tire pieces at a waste tire cutting facility is subject to the following restrictions:

(1) A bank of tire pieces may not be more than:

(A) twenty (20) feet high;

(B) fifty (50) feet wide; or

(C) one hundred fifty (150) feet long.

(2) Two (2) adjacent banks of tire pieces must be separated by a fire lane at least forty (40) feet wide.

(3) A bank of tire pieces must be at least one hundred (100) feet away from the boundary of the property on which the tire cutting facility is located.

(h) The commissioner shall issue a permit under this SECTION for the operation of a waste tire cutting facility to a person who applies for the permit, submits the description and written commitment required by subsection (b), and establishes an escrow account as required by subsection (d). A permit issued under this section is effective for:

(1) five (5) years; or

(2) the period requested in the permit application, if that period is less than five (5) years.

(i) The following shall be incorporated as the conditions applying to a permit issued under this SECTION:

(1) The requirement to pay an annual fee of one hundred dollars ($100), as set forth in subsection (c).

(2) The requirement to deposit a certain amount in the escrow account for each cubic yard of tire pieces stored at a facility, as set forth in subsection (d).

(3) The restrictions upon the storage of tire pieces set forth in subsection (g).

(j) This SECTION expires on the earlier of the following:

(1) July 1, 1992.

(2) The date on which rules adopted by the solid waste management board under IC 13-7-23-15 take effect.

SECTION 7. (a) A permit issued under SECTION 6 of this act is not rendered invalid by the expiration of SECTION 6 of this act. However, before or after the expiration of SECTION 6 of this act, the commissioner of the department of environmental management may modify or revoke a permit issued under SECTION 6 of this act in the manner set forth in IC 13-7-10-5 for the violation of any condition of the permit set forth in SECTION 6(i) of this act.

(b) Notwithstanding the expiration of SECTION 6 of this act, money deposited in an escrow account with respect to a waste tire cutting facility under SECTION 6(d) of this act shall remain in the escrow account until:

(1) the permit expires or is terminated and all waste tires and tire parts are removed from the site of the facility;

(2) the commissioner, under the circumstances referred to in SECTION 6(d) of this act, withdraws the money to pay for the removal of waste tires or tire parts; or

(3) financial responsibility for the potential costs of removing waste tires and tire parts from the facility is established through another means according to the rules adopted by the solid waste management board under IC 13-7-23-15.

(c) This SECTION expires July 1, 1997.

SECTION 8. (a) The solid waste management board shall adopt the rules required by IC 13-7-23.2-14, as added by this act, before July 1, 1992.

(b) This SECTION expires July 1, 1992.

SECTION 9. (a) Before July 1, 1991, the commissioner shall adopt guidelines for the issuance of permits under SECTION 6 of this act. The commissioner shall issue permits under SECTION 6 of this act according to the guidelines adopted under this SECTION until the expiration of SECTION 6 of this act.

(b) This SECTION expires July 1, 1992.

SECTION 10. Because an emergency exists, this act takes effect as follows:

SECTION 1	Upon passage
SECTIONS 2 through 5	July 1, 1991
SECTIONS 6 through 9	Upon passage

Appendix C

Information About Photograph Negatives

INFORMATION ABOUT NEGATIVES

Negatives for the following figures may be located in the Joint Highway Research Project office, Engineering Experiment Station, Purdue University, West Lafayette, Indiana:

Figure 5.1	A 12-inch diameter compression mold
Figure 5.2	Half-size, 12-inch diameter compression mold
Figure 5.3	The MTS Soil Testing System, with large size compression mold
Figure 5.4	The MTS Soil Testing System, with half-size compression mold
Figure 6.1	Preparation of a rubber-sand sample by vibratory compaction
Figure 6.2	A rubber-sand sample enclosed in rubber membrane and under a state of vacuum
Figure 6.3	A triaxial sample of 1-inch chips/sand mix at optimum ratio (≈ 39% chips)
Figure 6.4	A triaxial sample of 0.5-inch chips/mix at optimum ratio (≈ 39% chips)
Figure 6.5	A rubber-sand sample at chip/mix ratio of 44%
Figure 6.6	A rubber-sand sample at chip/mix ratio of 50%
Figure 6.7	A rubber-sand sample at chip/mix ration of 66.5%
Figure 6.8	A rubber-sand sample set up in 6-inch diameter triaxial cell
Figure 6.9	A 6-inch diameter triaxial cell mounted in the

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