



PB99-111932

GEOTECHNICAL INVESTIGATION OF THE POTENTIAL USE OF SHREDDED SCRAP TIRES IN SOIL STABILIZATION

Final Report

FHWA/OH-98/004

The Ohio Department of Transportation

and

The U.S. Department of Transportation,

Federal Highway Administration

REPRODUCED BY:
U.S. Department of Commerce **NTIS**
National Technical Information Service
Springfield, Virginia 22161

by

Abdul Shakoor and Chien-Jen Chu

**Department of Geology
Kent State University
Kent OH 44242**

1. Report No. FHWA/OH-98/004		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle GEOTECHNICAL INVESTIGATION OF THE POTENTIAL USE OF SHREDDED SCRAP TIRES IN SOIL STABILIZATION				5. Report Date December 17, 1997	
				6. Performing Organization Code	
7. Author(s) Abdul Shakoor				8. Performing Organization Report No.	
9. Performing Organization Name and Address Kent State University Water Resources Research Institute Kent, OH 44242-0001				10. Work Unit No. (TRAIS)	
				11. Contract or Grant No. State Job No. 14590(0)	
12. Sponsoring Agency Name and Address Ohio Department of Transportation 25 S. Front St. Columbus, OH 43215				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration					
16. Abstract Silt-tire and clay-tire mixtures, containing 0% to 100% shredded tire material by weight, with tire chips ranging in size from 7mm-13mm, 13mm-25mm, and 25mm-38mm, were tested for a series of engineering properties including compaction characteristics, permeability, unconfined compressive strength, friction angle, cohesion, and compression index. In addition, the leachate samples from shredded tire material, soil-tire mixtures, and a test embankment, containing 70% clay and 30% shredded tire material by weight, were analyzed for chemical composition. The results show that density and unconfined compressive strength decrease, and permeability increases, with increasing shredded tire content for both soil types and all three tire sizes used in the study. In general, the addition of shredded tire material improves the friction angle for both silt and clay by a few degrees but also increases their compression index values. The results of leachate analyses show that concentrations of trace elements from soil-tire mixtures are less than the maximum allowed contaminant levels specified in United States Environmental Protection Agency's regulations. Based on these results, soil-tire mixtures have the potential for use as a lightweight fill material for highway embankments as well as for stabilization of slopes. PROTECTED UNDER INTERNATIONAL COPYRIGHT ALL RIGHTS RESERVED. NATIONAL TECHNICAL INFORMATION SERVICE U.S. DEPARTMENT OF COMMERCE					
17. Key Words Shredded Scrap Tires, Soil-Tire Mixtures, Engineering Properties, Leachate Characteristics, Lightweight Fill Material				18. Distribution Statement No Restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages	22. Price



**Final Report
FHWA/OH-98/004**

**GEOTECHNICAL INVESTIGATION OF THE POTENTIAL USE OF SHREDDED
SCRAP TIRES IN SOIL STABILIZATION**

Sponsored by

The Ohio Department of Transportation

in cooperation with

**The U.S. Department of Transportation,
Federal Highway Administration**

Submitted by

Abdul Shakoor: Principal Investigator

Chien-jen Chu: Graduate research Assistant

Department of Geology

Kent State University

Kent OH 44242

November, 1998



ACKNOWLEDGMENTS

The research reported herein was supported by the Ohio Department of Transportation and the Federal Highway Administration, U.S. Department of Transportation. Mr. William F. Edwards and Mr. Roger L. Green served as the liaison officers between the Ohio Department of Transportation and Kent State University. Their administrative assistance throughout the execution of the project is gratefully acknowledged.

The shredded tire material for this study was provided by Continental Turf Systems of Continental, Ohio, and by Phoenix Recycling Industries, Inc., Columbus, Ohio. Bochert Excavating, Inc., of Kent, Ohio, helped in construction of the field embankment. We are thankful to all three companies for their assistance.

Thanks are also due to Karen Smith of the Department of Geology, Kent State University, Kent, Ohio, for proof reading and editing of this report.



TABLE OF CONTENTS

	Page
LIST OF FIGURES -----	viii
LIST OF TABLES -----	xi
ACKNOWLEDGMENTS -----	xiii
ABSTRACT -----	1
CHAPTER	
1. INTRODUCTION -----	4
1.1 Background Information -----	4
1.2 Previous Investigations -----	7
1.3 Objectives of the Study -----	15
2. METHODOLOGY -----	17
2.1 Collection and Preparation of Laboratory Samples -----	17
2.2 Laboratory Investigations -----	17
2.3 Field Investigations -----	21
2.3.1 Evaluation of Degradability -----	22
2.3.2 Evaluation of Test Embankment -----	22
2.4 Chemical Characterization of Scrap Tires and Soil-Tire Mixtures -----	24
2.5 Data Analysis -----	31

3.	ENGINEERING PROPERTIES OF SOILS, SHREDDED TIRE CHIPS, AND SOIL-TIRE MIXTURES-----	33
	3.1 Engineering Properties of Soils Used-----	33
	3.2 Engineering Properties of Shredded Tire Material Used -----	33
	3.3 Engineering Properties of Soil-Tire Mixtures-----	33
	3.3.1 Moisture-Density Relationships -----	33
	3.3.2 Permeability-----	47
	3.3.3 Strength Characteristics -----	55
	Friction Angle and Cohesion Parameters-----	55
	Shear Strength -----	60
	Unconfined Compressive Strength-----	63
	3.3.4 Consolidation Characteristics -----	67
	3.4 Degradation Analysis -----	71
	3.5 Summary of Results -----	73
4.	CONSTRUCTION AND PERFORMANCE OF THE SOIL-TIRE TEST EMBANKMENT-----	77
	4.1 Introduction -----	77
	4.2 Construction Process -----	79
	4.3 Instrumentation-----	86
	4.4 Performance -----	87
	4.5 Slope Stability Analysis -----	92
	4.6 Summary of Results -----	96

5.	CHEMICAL CHARACTERIZATION OF SHREDDED SCRAP TIRE AND SOIL-TIRE MIXTURES-----	98
	5.1 Introduction -----	98
	5.2 Background Information -----	98
	5.3 Chemical Analyses -----	99
	5.3.1 Loss on Ignition -----	100
	5.3.2 Bulk Analysis -----	100
	5.3.3 Chemical Analysis of Leachate from Laboratory Samples-----	105
	5.3.4 Chemical Analysis of the Leachate from the Field Samples -----	108
	5.3.5 Chemical Analysis of the Leachate from the Embankment Samples-----	113
	5.4 Discussion -----	116
	5.5 Summary -----	119
6.	ENGINEERING APPLICATIONS OF TIRE-STABILIZED SOILS -----	121
	6.1 Roadway Embankments -----	121
	6.2 Hydraulic Barriers, Landfill Liners, and Landfill Cover Material -----	122
	6.3 Football Fields and Playgrounds-----	124
	6.4 Lightweight Fill Material -----	124
	6.5 Economic Evaluation -----	127
7.	CONCLUSIONS AND RECOMMENDATIONS -----	129
	7.1 Conclusions-----	129
	7.2 Recommendations for Future Research -----	134

REFERENCES -----	135
------------------	-----

APPENDICES

A: Results of Compaction Tests -----	140
B: Results of Permeability Tests -----	164
C: Results of Tri-Axial Tests-----	166
D: Results of Unconfined Compression Tests-----	175
E: Results of Consolidation Tests -----	177
F: Settlement Data for the Test Embankment-----	187
G: Slope Angle Data for the Test Embankment-----	189
H: Results of LOI Tests -----	191
I: Results of Bulk Analysis Tests -----	193
J: Results of Leachate Analysis for Laboratory Samples-----	198
K: Results of Leachate Analysis for Field Samples -----	203
L: Results of Leachate Analysis for Embankment Samples-----	227

LIST OF FIGURES

Figure 3.1:	Maximum dry density versus shredded tire content for silt-tire mixtures. -----	36
Figure 3.2:	Maximum dry density versus shredded tire content for clay-tire mixtures. -----	37
Figure 3.3:	Optimum water content versus shredded tire content for silt-tire mixtures. -----	38
Figure 3.4:	Optimum water content versus shredded tire content for clay-tire mixtures. -----	39
Figure 3.5:	Optimum water content versus shredded tire content for silt-tire mixtures (linear plot). -----	45
Figure 3.6:	Optimum water content versus shredded tire content for clay-tire mixtures (linear plot). -----	46
Figure 3.7:	Permeability versus shredded tire content for silt-tire mixtures. -----	48
Figure 3.8:	Results of linear regression analysis for permeability versus shredded tire content for silt-tire mixtures. -----	49
Figure 3.9:	Permeability versus shredded tire content for clay-tire mixtures. -----	50
Figure 3.10:	Results of linear regression for permeability versus shredded tire content for clay-tire mixtures -----	51
Figure 3.11:	Friction angle versus shredded tire content for silt-tire mixtures. -----	56
Figure 3.12:	Friction angle versus shredded tire content for clay-tire mixtures. -----	57
Figure 3.13:	Cohesion versus shredded tire content for silt-tire mixtures. -----	58
Figure 3.14:	Cohesion versus shredded tire content for clay-tire mixtures. -----	59

Figure 3.15:	Shear strength versus shredded tire content for silt-tire mixtures.-----	61
Figure 3.16:	Shear strength versus shredded tire content for clay-tire mixtures. ----	62
Figure 3.17:	Unconfined compressive strength versus shredded tire content for silt-tire mixtures.-----	64
Figure 3.18:	Unconfined compressive strength versus shredded tire content for clay-tire mixtures.-----	65
Figure 3.19:	Compression index value versus shredded tire content for silt-tire mixtures.-----	68
Figure 3.20:	Compression index value versus shredded tire content for clay-tire mixtures.-----	69
Figure 4.1:	The grain size distribution of shredded tire, gravel, and foundation soil.-----	78
Figure 4.2:	The plan view (top) and cross-section (bottom) of the test embankment. -----	80
Figure 4.3:	An overview of the synthetic liner that was used to separate the foundation soil from the embankment materials. -----	81
Figure 4.4:	Covering of the perforated pipes by gravel soil to prevent piping of the clay soil into the holes. -----	83
Figure 4.5:	Rototiller, attached to a tractor, that was used to mix the soil and shredded tire material.-----	84
Figure 4.6:	The second drainage system near the middle portion of the embankment consisting of a perforated pipe placed in a trench perpendicular to the embankment axis and covered with gravel filter. -----	85
Figure 4.7:	Schematic cross sections of the four lysimeters.-----	88
Figure 4.8:	Overview of the test embankment; four white pipes on the top of the embankment indicate the positions of the lysimeters. -----	89

Figure 4.9: Settlement of embankment crest vs. days after construction. ----- 90

Figure 4.10: Slope angles of both sides of the embankment vs. time in day.
The vertical bar through each data point represents error range
of 2.5 degrees.----- 93

Figure 4.11: Relationships between slope height, slope angle, and factor of
safety. The numbers on the curves represent F.S. values. ----- 95

LIST OF TABLES

Table 2.1:	Physical parameters of ICP used in this research. -----	28
Table 2.2:	Physical parameters of GFAA used in this research. -----	29
Table 3.1:	Engineering properties of the soils used. -----	34
Table 3.2:	Dry density and permeability of shredded tire material. -----	34
Table 3.3:	F values for silt-tire mixtures containing different tire sizes, with different polynomial degrees. -----	41
Table 3.4:	F values for clay-tire mixtures containing different tire sizes, with different polynomial degrees. -----	41
Table 3.5:	R ² values of different subsets of optimum water content versus shredded tire content data for silt-tire mixtures. -----	43
Table 3.6:	R ² values of different subsets of optimum water content versus shredded tire content data for clay-tire mixtures. -----	44
Table 3.7:	R ² values of different subsets of permeability versus shredded tire content data for silt-tire mixtures. -----	53
Table 3.8:	R ² values of different subsets of permeability versus shredded tire content data for clay-tire mixtures. -----	54
Table 3.9:	F values for silt-tire mixtures containing different tire sizes, with different polynomial degrees and exponential function. -----	66
Table 3.10:	F values for clay-tire mixtures containing different tire sizes, with different polynomial degrees and exponential function. -----	66
Table 3.11:	F values for silt-tire mixtures containing different tire sizes, with different polynomial degrees. -----	70
Table 3.12:	F values for clay-tire mixtures containing different tire sizes, with different polynomial degrees. -----	70

Table 3.13.	Results of degradation test. -----	72
Table 4.1:	Engineering properties of the soil-tire mixtures used for embankment construction. -----	78
Table 5.1:	Results of loss on ignition (LOI) test. -----	101
Table 5.2:	Results of t-test performed to assess the effect of tire size on LOI value.-----	101
Table 5.3:	Results of normalized bulk chemical analyses.-----	102
Table 5.4:	Results of t-test to assess the effect of tire size on bulk chemistry. ----	104
Table 5.5:	Results of leachate analyses for leachate prepared in the laboratory. --	106
Table 5.6:	Results of t-test for leachate analysis to assess the effect of tire size range on the concentration of various elements.-----	107
Table 5.7:	The maximum concentrations of leachate from the field samples placed on the roof. -----	109
Table 5.8:	The length of time, in days, after which the maximum concentrations of various elements were observed in the leachate samples obtained from the field samples placed on the roof. -----	110
Table 5.9:	Results of chemical analysis of the leachate collected from the field embankment. -----	114
Table 5.10:	The length of time, in days, after which the maximum concentrations of various elements were observed in the leachate samples obtained from the embankment.-----	115
Table 6.1:	Cost comparison of soil-tire mixtures and other construction materials.-----	128



ABSTRACT

Currently, 2.5-3 billion scrap tires are stockpiled across the United States. Stockpiled scrap tires represent a waste of resources and a public health hazard. Also, landfilling of scrap tires is becoming impractical due to the rapidly decreasing disposal capacities of existing landfills. The best way to minimize, and ultimately eliminate, the landfilling and stockpiling of discarded tires is to find alternative uses. A large scale potential use of shredded scrap tires can be in soil stabilization, provided the mixtures exhibit the desired engineering properties and environmentally safe chemical characteristics.

Compaction characteristics, permeability, unconfined compressive strength, compressibility, and shear strength parameters were determined for two different soil types (a non-plastic silt and a low plasticity clay), three different size ranges (1/4"-1/2" or 7 mm-13 mm; 1/2"-1" or 13 mm-25 mm; 1"-1.5" or 25 mm-38mm) of shredded tire material, and soil-tire mixtures containing 10% to 90% shredded tire material by weight. The results show that most engineering properties improve with the addition of shredded tire material. The maximum dry density decreases linearly with an increase in shredded tire content for both soil types and all three tire chip sizes. The optimum water content decreases only slightly up to 60% tire content, beyond which it shows a rapid decrease from over 14% to less than 3% at 100% tire content for both soil types and all three tire chip sizes used. The permeability of soil-tire mixtures increases by six orders of magnitude with increasing shredded tire content for both soil types and all three tire chip sizes. The friction angle

increases with increasing tire content for silt-tire mixtures. For clay-tire mixtures, however, the friction angle increases up to 20% tire content and then decreases. The cohesion decreases with increasing tire content for both types of soil-tire mixtures containing 1/4"-1/2" (7 mm-13 mm) size shredded tire material. For soil-tire mixtures containing other two sizes of tire chips, the cohesion increases at 10% shredded tire content by weight, and then drops. The unconfined compressive strength decreases with an increase of shredded tire content for both soil types and all three size ranges of shredded tire. The compression index values increase with increasing amounts of shredded tire for both types of soil-tire mixtures. The degradation test revealed that the smaller tire chips and the higher soil proportion result in higher amount of tire degradation.

In addition to laboratory investigations of soil-tire mixtures, a test embankment, containing 30% shredded tire material and 70% clay soil by weight, was constructed and monitored for settlement, slope stability, and leachate composition. The embankment construction revealed that a rototiller is the most effective way of mixing soil and shredded tire material, whereas a sheepsfoot roller is the best equipment for compacting the soil-tire mixtures. During the one year monitoring period, the slope angles of the test embankment remained constant and the maximum settlement was approximately 6 inches (15 cm). The stability analysis indicates that the test embankment has a factor of safety of 4.1 under dry conditions and of 2.1 under saturated conditions.

The loss on ignition (LOI) test, bulk chemical analyses, and leachate analyses were performed for shredded tire material and soil-tire mixtures to evaluate the environmental

impact. Results of the LOI test and bulk chemical analyses show that there are no significant differences between the three shredded-tire size ranges. The bulk chemical analyses indicate that pure tire material has the potential to adversely affect the environment if the tire chips were to degrade completely and all components were to be released.

Three different methods were used to extract leachate samples: a laboratory method and two field methods (box samples placed on roof of Geology Department and embankment samples). The results of leachate analyses from the laboratory samples indicate that concentration of barium from shredded tire material may exceed the maximum contaminant levels (MCLs) specified in U.S. Environmental Protection Agency's regulations. The results of leachate analyses from the box samples indicate that soil-tire mixtures are less likely to contaminate the environment when the proportion of shredded tire material is less than 60%. The results of leachate analyses from embankment samples show that the concentrations of heavy metals are less than the MCLs and decrease with increasing depth.

Based on the engineering properties and chemical characteristics, soil-tire mixtures can be used as a construction material for roadway embankments, hydraulic barriers, and playgrounds, as well as a lightweight fill material. From an economic point of view, the cost of soil-tire mixtures is comparable to other construction materials.

CHAPTER 1

INTRODUCTION

1.1 Background Information

In the United States, over 279 million scrap tires are generated each year (House Bill S2462, 1990). Of these, nearly 85% are landfilled, stockpiled, or illegally dumped. This is equivalent to approximately 3.3 million tons of scrap tires each year and constitutes about 1.2% of the total solid waste stream (House Bill S2462, 1990). Currently, 2.5-3 billion scrap tires are stockpiled across the United States and scrap-tire dumps increase in size and number every year (House Bill S2462, 1990).

Although landfilling and stockpiling of scrap tires account for only 1.2% of the total solid waste stream, they cause significant environmental problems. When stockpiled, scrap tires provide an ideal breeding place for rats, mosquitoes, and other disease vectors, causing a public health hazard (Hudson and Lake, 1977; House Bill S2462, 1990). Mosquito borne diseases (encephalitis, yellow fever, etc.), associated with stockpiling of scrap tires, cost approximately \$5.5 million a year (House Bill S2462, 1990).

Stockpiling of tires can also result in fire hazards which are generally very severe and widespread. Burning scrap-tire fires are extremely difficult to extinguish and pose a serious threat to health and the environment due to liquid and gaseous emissions. The annual cost of extinguishing these fires exceeds 2 million dollars (House Bill S2462,

1990). In addition to environmental and health hazards, stockpiling and illegal dumping of scrap tires completely destroy the aesthetics of the surrounding areas.

The main problem associated with landfilling of scrap tires is their light weight and high durability. To provide the performance required for today's driving conditions, tires are manufactured to be very durable, which allows scrap tires to maintain their bulky shape and basic properties long after they are discarded. Because of their light weight and high durability, whole tires do not compact well and tend to rise to the surface of the landfill where they disrupt the landfill cap and allow water to infiltrate the landfill. Special procedures must be followed to overcome this problem, such as placing tires together at the bottom of the cells, or shredding tires before landfilling [Environmental Protection Agency (EPA), 1991]. However, because active landfills are rapidly reaching their maximum disposal capacities, landfilling of scrap tires may not be a viable option in the future. Also, it is becoming increasingly difficult to find new landfill sites due to environmental concerns and public opposition to their construction.

The best way to reduce the environmental and health hazards associated with scrap tires is to minimize, and ultimately eliminate, the landfilling and stockpiling of scrap tires. This can be accomplished, in part, by finding alternate uses for scrap tires. So crucial is this need that four bills pertaining to scrap tires are currently pending in the US Congress, and recently nine states have adopted new laws regulating the disposal and recycling of scrap tires (House Bill S2462, 1990). The need to find alternative applications for scrap tires is further evident from the fact that federal legislation was adopted in 1991 requiring

asphalt in federally funded highway projects to contain at least 5% rubber by 1994. The required percentage is expected to increase to 20% by the year 2000. In 1997, there have been over 70 projects that have used tire chips as fill material beneath roads. Each project consumed 0.6 million tires on the average and the total consumption has been approximately 12% of the number of scrap tires generated annually (Whetten et al., 1997; Scrap Tire Management Council, 1997).

At present, only 10% of the scrap tires find other productive usages such as breakwater pads (Kowalski and Ross, 1975; Tuan, 1988), artificial reefs (Stone et al., 1974; EPA, 1991), energy-absorbing abutments for bridges (EPA, 1991), incineration for steam generation (Moats, 1976; EPA, 1991), a supplementary fuel source [Taggart, 1975; EPA, 1990; Hemphill, 1990; Rubber Manufacturers Association (RMA), 1990], joint sealing material (Cleary and Clark, 1973; Goddard, 1975), and a constituent in rubber-modified asphalt concrete (RUMAC) and asphalt emulsions [Brand, 1974; Stephens and Mokrzewski, 1974; New York State Department of Transportation (NYSDOT), 1990; RMA, 1990; Biocycle, 1991; EPA, 1991; Eldin and Senouci, 1993].

Another large-scale potential use of scrap tires can be in soil stabilization. Shredded tires are already being used on a limited scale to improve football fields in Colorado, Michigan, and Pennsylvania where such applications consume as many as 12,000 tires to treat a single football field (Biocycle, 1990). This suggests that use of shredded tires in soil stabilization can create a major dent in the scrap tire glut. Shredded scrap tires can be mixed with poor quality soils to improve their desired engineering properties for certain

applications. In highway engineering, tire-stabilized soils may be used as a lightweight, or semi-lightweight, fill material for embankments and for reconstruction of potentially unstable or failed slopes. The results of recent studies (Read et al., 1991; Ahmed, 1992; Lamb, 1992; Bosscher et al., 1993; Upton and Machan, 1993; Black and Shakoor, 1994; Foose et al., 1996) suggest the potential for such applications.

There is some concern about the potential environmental impact of using shredded scrap tires. The possibility of toxic substances leaching from the material upon interaction with water may pose a threat to surface and ground water resources. Different conclusions have been reached by previous researchers based on their results of chemical analyses of shredded scrap tires. Some studies suggest that the shredded tires, when used in civil engineering applications, would not be a hazardous material (Grefe, 1989; RMA, 1990; Edil and Bosscher, 1992; Bosscher et al., 1993) but other studies show that the concentrations of some elements may exceed the levels permitted by EPA [Minnesota Pollution Control Agency (MPCA), 1990; Black and Shakoor, 1994].

1.2 Previous Investigations

Only a few laboratory studies dealing with qualitative and quantitative information on the engineering properties of tire chips, and soil-tire mixtures, are available in the literature (Bressette, 1984; Edil, et al., 1990; Ahmed, 1992; Black and Shakoor, 1994; Foose et al., 1996). Bressette (1984) performed permeability tests on chopped tire material (greater than 2" or 5 cm in size) and shredded tire material (less than 2" or 5 cm in size) in compacted and uncompact states. In both states, permeability values for chopped tire

material and shredded tire material were 1.38 inch/sec (3.53 cm/sec). The results are comparable to permeability values of Class III coarse aggregate and represent the upper range of permeability values required for sub-basecourse drainage material (Bressette, 1984). Besides permeability, the density, cohesion, and friction angle values were determined for both materials. The chopped material and the shredded material exhibited a minimum density of 25.6 pcf (0.41 Mg/m^3) and a maximum density of 35.3 pcf (0.57 Mg/m^3). On average, the chopped tire chips had a cohesion of 540 psf (2.64 Mg/m^2) and a friction angle of 21° whereas the shredded tire chips had a cohesion of 660 psf (3.22 Mg/m^2) and a friction angle of 14° (Bressette, 1984).

Edil et al. (1990) analyzed the consolidation behavior of tire chips and sand-tire mixtures. The sand-tire mixtures varied from 100% sand to 100% chips. The tests on tire-sand mixtures yielded compression (e-log p) curves similar to those of rubber chips alone. The compressibility increased significantly when tire chip content was increased beyond 30% by weight of sand.

Ahmed (1992) investigated the compactive behavior of soil-tire mixtures as a construction material for highway embankments. He used a poorly graded sand (SP) and a silty clay (CL-ML), each mixed with tire chips ranging in size from 0.19" to 1.95" (4.75 mm-5 cm). The proportions of soil and tire chips varied from pure soil to pure tire chips. The vibration method [American Society for Testing and Materials (ASTM) D4253] was used to compact sand-tire mixtures. For clay-tire mixtures, three different compactive methods were used: (1) modified Proctor method (ASTM D1557), (2) standard Proctor

method (ASTM D698), and (3) standard Proctor method with the number of blows per layer adjusted to give the compactive effort equivalent to 50% of the standard Proctor method. Ahmed (1992) found that the dry density was not sensitive to the size of chips but the dry density of soil-tire mixtures decreased with increase of tire content. The compactive effort did not seem to increase the dry density of pure tire material. The vibration method was found to be most suitable for the sand-tire material and the Proctor type compaction for the clay-tire material.

Black and Shakoor (1994) investigated the engineering properties and chemical characteristics of soil-tire mixtures including three different types of soil (sand, silt, and clay) and three different sizes of shredded tire (<0.04" or <1 mm; 0.04"-0.16" or 1 mm-4 mm; and 0.16"-0.27" or 4 mm-7 mm). The results showed that the maximum dry density and unconfined compressive strength of soil-tire mixtures decreased, and permeability increased, with increasing shredded tire content. The addition of shredded tire improved the friction angle for silt and the cohesion values for sand and clay. Their research revealed that the engineering properties of soil-tire mixtures were really affected by size and proportion of shredded tire material.

Foose et al. (1996) performed direct shear tests to investigate the shear strength characteristics of sand reinforced by shredded tire material of sizes <2" (<5 cm), 2"-4" (5 cm-10 cm), and 4"-6" (10 cm-15 cm) size. Several factors, including normal stress, dry density of pure sand, shredded tire content, shredded tire sizes, and orientation of tires shreds tires, were considered in their study. They found that three factors including normal

stress, dry density of pure sand, and shredded tire content affected the strength of reinforced sand. Addition of shredded tire material to sand increased the friction angle and the shear strength. Mixtures with a higher dry density of sand had a higher rate of increase of the friction angle than did mixtures with a lower dry density of sand.

Little research has been done to investigate degradation of tires over time (Jones et al. 1974; Crane, et al. 1978; Cadle and Williams, 1980). Jones et al. (1974) designed a method of measuring the change of oxygen pressure from soil charged with varying quantities of rubber fragments. From the results, they concluded that rubber fragments were oxidized biologically by micro-organisms in natural soil. Crane et al. (1978) suggested that certain tire components, such as zinc oxide, antidegradants, and vulcanization accelerators, could restrict the growth of micro-organisms and decrease the degradation rate. Cadle and Williams (1980) claimed that a variety of factors such as heat, oxygen, ozone, light, humidity, and micro-organisms affect the rate of degradation. In order to evaluate those factors, they employed three methods including extraction-pyrolysis-GC, pyrolysis-GC, and thermogravimetric analysis (TGA) on the rubber particles and the rubber particles recovered from the soil-tire mixtures. The results showed that biodegradation did not reduce the total carbon content of the tire particles during the sixteen months of exposure. Oxidation could have oxidized the polynuclear hydrocarbons present in the oil. Therefore, over one-half of the extender oil present in the tire was oxidized sufficiently. The results suggest that micro-organism attack of tire particles is less significant than attack by atmospheric oxygen. Based on these results, Cadle and Williams

(1980) suggested that the oxidation is a more effective process to degrade tires to soil-like material.

The field research done to evaluate the possibility of using tire chips (Read et al., 1991; Lamb, 1992; Bosscher et al., 1993; Upton and Machan, 1993) is even more limited than the laboratory studies. Read et al. (1991) performed the deflection tests to evaluate the possibility of using tire chips as a subgrade material for pavements. These authors indicated that the average deflection of the pavement over the rubber tire fill was approximately 0.02 inch (0.5 mm) as compared to a typical deflection of 0.01 inch (0.25 mm) normally measured for a similar asphalt-aggregate base pavement constructed over soil subgrade.

Lamb (1992) provided data obtained from settlement plates placed both at the bottom and top of shredded tire fill used as the subgrade of a road in Eden Prairie, Minnesota. The data indicated that this roadway settled an average of 0.9 inches (23 mm) per year overall, and just 0.4 inches (10 mm) per year at the bottom of the tire fill, 19 months after construction. Lamb (1992) also reported that post-construction settlement in Milaca, Minnesota was 40% to 50% less than anticipated.

Bosscher et al. (1993) performed field experiments to evaluate the use of shredded tire material as a replacement for highway embankments. A 20-foot (6 m) long, 16-foot (5 m) wide, and 6-foot (2 m) high test embankment made of shredded tire material was constructed. The embankment consisted of a total of eight study sections composed of either different soil-tire mixtures or constructed by using different compactive method. The test embankment was exposed to heavy truck traffic and field data were collected to

assess the stability and deformation characteristics of the embankment, and the compaction characteristics of the tire chips. Based on the results of settlement, the overall performance of the embankment was considered to be similar to that of most gravel roads. Comparing the performance of the eight sections, the section which was covered by a thicker cap of soil performed better than the section which was covered by a thinner cap of soil. The results also indicated that normal construction machinery could be used successfully with tire chips, even though rubber tires on construction equipment can be punctured by the wire exposed at the edges of the chips. Vibration or static compaction did not significantly increase compaction of tire chips. Bosscher et al. (1993) concluded that the use of tire chips as a lightweight fill in highway applications, if properly confined, was a feasible option.

Upton and Machan (1993) used monitoring devices, including two inclinometers, two settlement plate installations, and three rows of survey monuments to perform their field tests. The settlement plate data reflected compression of 15% of the 12-foot (3.6 m) thick shredded tire fill under the soil and pavement surcharge. The survey monument data indicated greater settlement near the center of the shredded tire fill and less toward the ends. Upton and Machan (1993) also presented the results of a study of tire chips with a soil cap used in a pavement in southern Oregon. The results indicated that the pavement section over the shredded tire fill met the 20-year design life criteria, however, it deflected more than a similar pavement section over an earth embankment.

Another area of interest with respect to field operations has been the type of equipment

required for compacting shredded tire material and soil-tire mixtures. It is well known that clay soils are best compacted by sheepsfoot rollers, tamping-foot rollers, and grid pattern rollers whereas gravel, sand, and aggregate material are best compacted by smooth-wheel rollers, rubber-tired rollers, and vibratory equipment (Holtz and Kovacs, 1981; Ohio Department of Transportation, 1989). Most of the previous research used only pure shredded tire material for construction of embankments because it can be compacted adequately using smooth-wheel rollers, rubber-tired rollers, and vibratory equipment. However, no information is available as to which method and equipment are most suitable for mixing shredded tire material with soils and compacting the mixtures properly.

A few studies relating to the evaluation of environmental impact of using scrap tires have been presented (Grefe, 1989; MPCA, 1990; RMA, 1990; Edil and Bosscher, 1992; Bosscher et al., 1993; Black and Shakoor, 1994). Grefe (1989) used the American Foundry Society (AFS) procedure to analyze leachate extracted from a tire chip embankment. He reported that the concentrations of Zn and Pb were below the maximum contaminant levels (MCLs) when the pH was equal to 5.5.

The Minnesota Pollution Control Agency (MPCA, 1990) performed four leachate tests with different pH conditions (pH = 3.5, pH = 5.0, pH = 7.0, and pH = 8.0). The leachate tests used EPA Method SW-846-1310 as a leachate preparation model. The concentrations of the elements including silver, aluminum, arsenic, barium, calcium, cadmium, chromium, iron, mercury, magnesium, lead, sulfur, selenium, tin, and zinc were examined, using inductively coupled plasma (ICP) spectrometer and graphite furnace

atomic absorption (GFAA) techniques. The results of chemical analyses indicated that generally higher concentrations of metals were present when the pH of the extraction fluid was low (MPCA, 1990). The concentration of metals which exceeded the MCLs were cadmium, chromium, lead and zinc at a pH of 3.5. Therefore, MPCA (1990) concluded that scrap tires were a hazardous waste material.

Rubber Manufacturers Association (RMA, 1990) performed chemical analyses for various types of tires. The leachate was extracted while the value of pH was 5.5 and tested for metals including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver were performed. Only four elements (barium, chromium, lead, and mercury) were detected. All results were reported to be below the MCLs (RMA, 1990).

Edil and Bosscher (1992) sampled leachates from two lysimeters installed in an embankment composed of pure tire chips ranging from 2 inches to 4 inches (5 cm-10 cm). They tested the leachate for hardness, total solids, alkalinity, and elements including barium, calcium, chlorine, iron, lead, mercury, manganese, sodium, and zinc. Four metallic elements (barium, iron, manganese, and zinc) exhibited increasing concentrations over time while the pH varied from 7.5 to 7.7. The highest concentrations for iron and manganese were around the MCLs, while those for barium and zinc were below the MCLs (Edil and Bosscher, 1992).

Bosscher et al. (1993) collected leachate samples from a lysimeter installed in an embankment composed of 2"x3" (5 cm x 7.6 cm) pure tire chips. During the first six months, the samples were collected on a monthly basis and then quarterly. The value of pH ranged from 7.1 to 7.9. The concentrations of inorganic elements including barium,

manganese, lead, and zinc were found to be less than the MCLs (Bosscher et al., 1993).

Black and Shakoor (1994) performed bulk chemical analysis and leachate extraction tests in accordance with the EPA method SW-846-1310 (EPA, 1990). The bulk chemical analyses consisted of analyzing for elements including iron, cadmium, lead, zinc, and copper whereas the leachate samples were analyzed for barium, iron, cadmium, chromium, lead, and zinc under pH = 5 condition. The results of the leachate analyses showed that the concentrations of chromium, iron, and zinc exceeded the MCLs as specified by EPA in Federal Register CFR57 (EPA, 1992) for all three tire sizes (<0.04" or <1 mm; 0.04"-0.16" or 1-4 mm; and 0.16"-0.27" or 4-7 mm). The concentrations of leachate samples from the smallest shredded tire size (<0.04" or <1 mm) exceeded the MCLs for all tested elements.

1.3 Objectives of the Study

In order to use shredded scrap tires for soil stabilization, research was needed to determine the optimum size and proportion of shredded tire for soil stabilization purposes and to extend the results of laboratory investigations to field applications. Another concern was how to best mix the soil and shredded tire material during field applications. Of additional interest was possible degradation of shredded tire material over time which may result in deterioration of the beneficial properties of tire-stabilized soils. Still another concern was the potential for toxic substances to leach from the material upon interaction with water.

It was desirable that research to address these concerns be conducted in a comprehensive study which examined the engineering properties, field applications,

chemical characteristics, and economic aspects of tire-stabilized soils. Previous works have addressed some of these concerns but no comprehensive study is available on use of shredded tire material for soil stabilization.

In order to propound a complete procedure for using shredded tire material in soil stabilization, the specific objectives of this research were to:

1. Investigate the effects of shredded tire size and proportion on the geotechnical properties of soil-tire mixtures.
2. Determine the chemical characteristics of the leachate generated by the interaction of water and various soil-tire mixtures.
3. Evaluate the durability of shredded tire and soil-tire mixtures under varying climatic conditions.
4. Evaluate the field performance of a test embankment made of tire-stabilized soil.
5. Evaluate the practical aspects of construction procedures (mixing, placing, compacting) .
6. Evaluate the potential applications of tire-stabilized soils in highway engineering as well as the economic implications of such applications.

CHAPTER 2

METHODOLOGY

2.1 Collection and Preparation of Laboratory Samples

Two different types of soil were used for the laboratory study: a silt and a clay. Bulk samples of the two soils, weighing about 1000 lbs (454 kg) each, were collected from local borrow areas. The samples were oven dried at 105°C for 24 hours, cooled to room temperature, and stored in air-tight plastic bags before they were subjected to various tests.

Samples of shredded tire were obtained from Continental Turf Systems, Inc., Continental, Ohio. The samples included three different size ranges: 1/4"-1/2" (7 mm-13 mm), 1/2"-1" (13 mm-25 mm), and 1"-1.5" (25 mm-38 mm). Approximately 500 lbs (227 kg) of shredded tire material was obtained in each size range for the laboratory tests.

2.2 Laboratory Investigations

The silt and clay soils were tested in the lab to determine their engineering properties including Atterberg limits, compaction characteristics, permeability, shear strength parameters, and consolidation behavior. The three size ranges of shredded tire material were tested for compaction characteristics and permeability.

Mixtures of soil and shredded tire, containing 10% to 90% shredded tire by weight, were prepared using each of the two soil types and each of the three size ranges of

shredded scrape tire. The soil-tire mixtures were tested for compaction characteristics, permeability, shear strength parameters, unconfined compressive strength, and consolidation behavior. The following tests were performed to determine the aforementioned properties in accordance with the standard procedures of the American Society for Testing and Materials (ASTM, 1993).

Atterberg Limits Test (ASTM Procedure D4318)

Atterberg limits (liquid limit, plastic limit, and plasticity index) are the water contents at which marked changes in the engineering behavior of fine-grained soils occur (Holtz and Kovacs, 1981). They also indicate the plasticity characteristics of a material. In this study, Atterberg limits were used to classify the silt and clay soils as well as to evaluate the sensitivity of these soils to wetting and drying.

Compaction Test (ASTM Procedure D698)

The standard proctor test was used to determine the maximum dry density and optimum water content values for pure soils, shredded tire material, and various soil-tire mixtures. The procedure consisted of compacting samples of varying water contents in three layers, using a 4 inches (10.2 cm) diameter mold with each layer receiving 25 blows from a 5-lb (2.3 kg) hammer falling through 12 inches (30 cm). Engineering properties of soils and soil-like materials depend on density, with most properties improving with increasing density. The maximum dry density of a given soil is achieved at a certain water content referred to as the optimum water content. For a given compactive effort, the moisture-density relations are established to determine the maximum dry density (MDD)

and optimum water content (OWC). The results of the compaction test were particularly useful in evaluating the application of soil-tire mixtures as a fill material.

Permeability Test (ASTM Procedure D2434)

Permeability was measured on soil, tire chips, and soil-tire mixtures compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. Constant head test (ASTM Procedure D2434) was used to measure the permeability of shredded tire material and soil-tire mixtures which had high tire contents ($\geq 40\%$ for silt and $\geq 30\%$ for clay). For silt, clay, and soil-tire mixtures of low tire contents ($< 40\%$ for silt and $< 30\%$ for clay), the falling head test, as described by Holtz and Kovacs (1981), was used to measure the permeability. Permeability is an important property in evaluating the drainage characteristics of soil-tire mixtures and their suitability as a fill material for embankments and slopes.

Unconfined Compression Test (ASTM Procedure D1633 - Method A)

This test was performed on the two soils and soil-tire mixtures compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. The test results were used to determine the proportion of shredded tire material in each shredded tire-size range that is necessary to yield an adequate value of compressive strength for silt-tire and clay-tire mixtures. Compressive strength is used as an indicator of the structural stability of the tire-stabilized soils in different engineering applications.

Triaxial Test (ASTM Procedure D4767)

Triaxial test was performed to determine the shear strength parameters (cohesion and

friction) of the two soil types and various soil-tire mixtures. Consolidated-undrained (CU) version of the triaxial test was chosen for this study. In the CU test, the sample is first consolidated under the desired consolidation stress. Once the consolidation stage is complete, the drainage valves are closed, and the sample is loaded to failure without allowing any drainage to occur during the shearing stage (Holtz and Kovacs, 1981). The specimens for the triaxial test were compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. Since the height-to-diameter ratio for the test sample should be between 2 and 2.5 (ASTM Procedure D4767) (ASTM, 1993), a specially prepared mold with a height of 8.5" (21.6 cm) and a diameter of 4.1" (10.3 cm) was used to compact the samples in this test. Also, since the two larger size ranges [1/2"-1" (13 mm -25 mm) and 1"-1.5" (25 mm-38 mm)] of shredded tire contained steel wires, which punctured the rubber membrane and lead to leakage, only mixtures containing the smallest size range [1/4"-1/2" (7 mm-13 mm)] of shredded tire were subjected to this test initially. For soil-tire mixtures containing 1/2"-1" (13 mm-25 mm) and 1"-1.5" (25 mm-38 mm) tire sizes, respectively, a modified method was employed to measure the strength properties. The modification consisted of placing an extra, thicker rubber membrane around the original membrane containing the specimen in an attempt to provide additional protection against puncturing by steel wires. The shear strength parameters obtained from the test were used to determine the stability of soil-tire mixtures when placed on sloping surfaces.

Consolidation Test

The consolidation test was performed on samples compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. Due to size limitations of the test specimen (diameter 2.5"; height 1") used in the standard consolidation test (ASTM Procedure D2435), the standard test was not suitable to study the consolidation behavior of soil-tire mixtures containing different sizes of shredded tire in this research. For this reason, the consolidation characteristics were evaluated from the volume change data obtained during the consolidation stage of the triaxial testing of soil and soil-tire mixtures. The observed volumetric decrease was used to calculate the void ratio of consolidated soil-tire mixtures. A plot of void ratio versus principal stress difference was used to calculate the compression index. In order to validate this procedure, the compression index values computed from the triaxial test data were compared with those obtained from the standard test (ASTM D2435) for the pure soil samples (silt and clay) to get a calibration function that was then used to adjust compression index values obtained from the triaxial test. The compression index of soils and soil-like materials is an important property for evaluating their settlement upon loading.

2.3 Field Investigations

The purpose of the field investigation stage of this research was to evaluate the degradability of the shredded tire material, the stability of a test embankment made of tire-stabilized soil, and the practicality of various aspects of construction operations (mixing, placing, compacting, economic feasibility, etc.).

2.3.1 Evaluation of Degradability

In this study, the degradation of shredded tire material was evaluated in terms of the change in particle size over time, when exposed to varying climatic conditions. The soil-tire mixture with a particular tire size, or a particular ratio of soil and tire chips, was placed in a 1.5' x 1.5' x 1.5' (45.7 cm x 45.7 cm x 45.7 cm) plastic box. The plastic box was then placed on the roof of the Geology Department (McGilvrey Hall) of Kent State University for a period of 18 months. At the end of the 18-month period, the tire material was sieved through the same sieve on which it was retained when the experiment began. The ratio of the weight of the material passing the sieve to the initial weight, expressed as a percentage, was taken as a measure of degradation for the size range used. The degradation experiment was performed on all three size ranges of shredded tire as well as on selected soil-tire mixtures. The experiment involved a total of six plastic boxes: three for the pure shredded tire material and three for the soil-tire mixtures [clay mixed with 30% and 60% of 1/4"-1/2" (7 mm-13 mm) size tire chips by weight, and silt mixed with 30% of 1/4"-1/2" (7 mm-13 mm) size tire chips by weight]. Each box was provided with an outlet at the bottom for the leachate to escape.

2.3.2 Evaluation of Test Embankment

A test embankment was constructed on University property to evaluate the field performance of rubber-stabilized soils. The embankment material consisted of a mixture of the clay soil and 1/2"-1" (13 mm-25 mm) size shredded tire material used in the laboratory

study. The proportion of shredded tire material in the mixture was approximately 30% and was chosen on the basis of the properties determined in the laboratory. The following specifications and dimensions were used for embankment construction:

Density	> 95% of MDD
Water Content	$\pm 2\%$ of OWC
Lift Thickness	1 foot (0.3m)
Length	50 feet (15m)
Height	4.5 feet (1.5m)
Crest Width	8 feet (2.4m)
Bottom Width	22 feet (6.6m)
Side Slopes	33° and 36°

Two methods of mixing soil and shredded tire (a dozer and a large-size rototiller) were tried in the field before constructing the test embankment. The purpose here was to evaluate which method provided an even mixing of the two materials. In addition, the effects of factors such as water content and lump size of the clay material, the bulk quantities in which rubber was added to the soil, and the timing of rubber addition (before placement or during placement) were evaluated. The field study also investigated the type of roller (smooth wheel versus sheepsfoot) best suited for compacting rubber-stabilized soils and the practical problems encountered during construction when rubber soils were involved.

The stability of the test embankment was monitored for a period of one year. During

the first six months, the observations including the stability of the side slopes, settlement of the crest, development of tension cracks, and any other signs of deterioration were made twice a month and then once a month. Heights of the nine surface markers, used to assess settlement, and the slope angles of the embankment were measured at regular intervals. A Wild T-2 theodolite was used to measure the heights of the surface markers whereas a Brunton compass was used to measure the slope angles of the embankment. The results from these surveys permitted a qualitative/quantitative evaluation of the performance of the embankment.

In addition, the stability of the embankment slopes was analyzed quantitatively for both dry and wet conditions using the STABL4M computer program. The program was also used to determine factor of safety values for embankments constructed of 70% soil-30% tire mixtures but of varying heights and slope angles.

2.4 Chemical Characterization of Scrap Tires and Soil-Tire Mixtures

The purpose of chemical analyses was to determine whether the leachates from pure tire and soil-tire mixtures exceeded the tolerance limits set by EPA for hazardous wastes (EPA, 1992). Information about chemical characteristics was essential for evaluating the environmental impact of soil-tire mixtures in engineering applications. The mixtures can be considered environmentally safe only if the leachate does not have the potential to contaminate surface and ground water resources.

Chemical analyses were performed to determine the loss on ignition (LOI), the bulk chemistry, and the leachate characteristics of the shredded tire material and soil-tire

mixtures. ASTM method D2974 was used to determine the loss on ignition which represents the loss of hydrocarbons. Loss on ignition was taken as the percentage of initial weight of sample lost due to ignition of the sample at a high temperature. Samples were put into a muffle furnace set at a temperature of approximately 1000 °F and remained there until they were completely ashed. The initial tire weight and the ash weight after ignition were recorded to calculate the percent loss on ignition. Twenty samples of shredded scrap tire for each size range were used in these tests to verify whether differences between different tire sizes existed.

For performing the bulk analysis, the shredded scrap tire sample of a given size range, weighing approximately 1 gm, was burned in a muffle furnace at approximately 1000 °F for one hour. The ash was then washed into a 250 ml beaker with a minimum amount of deionized distilled water (DDIW), dissolved in 50 ml of 5% nitric acid, and stirred for two hours until no solid matter was observable. The solution was then transferred to a 100 ml volumetric flask and brought to 100 ml using DDIW. The resulting solution for each sample was filtered through a 45 µm polycarbonate filter. After filtration, the sample was stabilized by a addition of a 0.5 ml HNO₃ to prevent losses by sorption or co-precipitation. The extract solution was analyzed using an inductively coupled plasma (ICP) spectrometer for aluminum, barium, calcium, manganese, iron, and zinc; and using graphite furnace atomic absorption (GFAA) spectrophotometer for cadmium, chromium, cobalt, copper, and lead. Since a high concentration of zinc was expected in bulk chemical analysis, as previously noted by Black and Shakoor (1994), zinc was analyzed using ICP equipment.

Twenty samples of shredded scrap tire for each size range were used in these analyses to verify whether differences in chemical composition existed between different tire chip sizes.

Three types of leachate samples were obtained to evaluate the environmental impact of shredded scrap tire usage. In the first type, leachate was generated in the laboratory following the EPA Method SW-846-1310 (EPA, 1990) for all three size ranges of shredded tire material. Each sample consisted of 50 grams of shredded tire in 800 ml of deionized distilled water (DDIW). The solutions were shaken for a period of 24 hr., while maintaining the pH of the solution at 5 ± 0.2 by the manual addition of 0.5 N nitric acid. The resulting solution for each sample was filtered through a 45 μm polycarbonate filter. After filtration, the sample was stabilized by a addition of a 0.5 ml HNO_3 to prevent losses by sorption or co-precipitation. Twenty samples of shredded scrap tire for each size range were used in these analyses to verify whether differences in chemical composition existed between different tire sizes.

The other two types of leachate were the products of water-tire interaction in the field. The first type of leachate collection system in the field involved a total of six sample groups. Three of them were the three size ranges of pure shredded tire material and others were the soil-tire mixtures (silt mixed with 30% shredded tire by weight, and clay mixed with 30% and 60% shredded tire by weight, respectively). For each group, the material was put into a 18" x 18" x 18" (46 cm x 46 cm x 46 cm) plastic box. Each box was provided with an outlet at the bottom for the rain water to escape. The plastic boxes were

placed outside, on the roof of the Geology Department (McGilvrey Hall), and the leachate samples were collected periodically from each box for a period of 18 months. The pH and temperature of the samples were recorded at all sampling times using a pocket pH meter (Corning Pocket-size pH sensor, Model PS-15) and a pocket thermometer (Weksler Pocket Case Thermometer). The collected samples of 100 ml were stabilized by the addition of a 0.5 ml HNO_3 to prevent losses by sorption or co-precipitation and stored in a refrigerator. The second type of leachate collection system in the field consisted of installing four lysimeters, along the center line of the test embankment, reaching depths of 1, 2, 3, and 4 feet (0.3m, 0.6m, 0.9m, and 1.2m), respectively, from the embankment top. The leachate was collected periodically from those lysimeters for a period of one year. The pH values and temperature of the leachate samples were recorded each time using the pH meter and the thermometer as stated above. The collected samples of 100 ml were stabilized by the addition of a 0.5 ml HNO_3 to prevent losses by sorption or co-precipitation and stored in a refrigerator.

The ICP located on the third floor of the McGilvrey Hall, Kent State University, is an Instrumentation Laboratories Plasma 200 spectrometer. The physical parameters including argon pressure in the instrument, argon gas flow rates, and wavelengths are listed in Table 2.1. The drifting correlation was done by using a program developed by Dahl (1990). The GFAA located on the third floor of the McGilvrey Hall, Kent State University, is a Perkin-Elmer Model 5100 PC Atomic Absorption Spectrophotometer equipped with a HGA 600 Graphite Furnace, an AS 60 furnace autosampler, and a Zeeman 5100 PC furnace module. All analyses were performed at Kent State University. The wavelengths used for each

Table 2.1: Physical parameters of ICP used in this research.

Rf generator power	1.2 kw
Argon Pressure	60 psi
Argon Gas Flow Rates	13 l/min
Torch Height	12 mm
Sample Pumping Rate	1.0 ml/min
Integration Time	3.0 sec

Element	Wavelength (nm)	No. of Readings/analysis
Al	309.28	3
Ba	455.40	3
Ca	393.37	3
Cd	228.80	3
Co	238.89	3
Cr	267.71	3
Cu	324.75	3
Fe	238.20	3
Mn	257.61	3
Zn	213.86	3

Table 2.2: Physical parameters of GFAA used in this research.

Element	Wavelength (nm)	No. of Readings/analysis
Al	396.2	3
Ba	553.6	3
Cd	228.8	3
Co	242.5	3
Cr	357.9	3
Cu	324.8	3
Fe	248.3	3
Mn	279.5	3
Pb	283.3	3
Zn	213.9	3

element are listed in Table 2.2 while other standard conditions, as described in Perkin-Elmer (1985), were used without modification. Each sample was analyzed once. Three readings were taken in each analysis and the average value was used to represent the result of analysis.

The leachate samples prepared in the laboratory were analyzed using an ICP for aluminum, barium, calcium, manganese, and iron, and using GFAA spectrophotometer for cadmium, chromium, cobalt, copper, lead, and zinc. The leachate samples from the six boxes were analyzed for selected trace metals (aluminum, barium, calcium, cadmium, cobalt, chromium, copper, iron, manganese and zinc) using ICP and for lead using GFAA. All leachate samples from the test embankment were analyzed for aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc by using ICP and for lead by using GFAA before 11/1/96. Because of a breakdown of the ICP equipment in November, 1996, all elements were analyzed in GFAA after 11/1/96. A reference standard and a blank were prepared in an identical manner using 100 ppm for each of calcium, manganese, iron, and zinc and 10 ppm for each of aluminum and barium in ICP analysis, and 1, 10, 100 ppb for each of barium, manganese, iron, and zinc, and 1, 2, 5, 10 ppb for each of aluminum, cadmium, cobalt, chromium, copper and lead in GFAA analysis. Two kinds of detection limit, including an ideal one provided by the equipment manufacturer (Instrumentation Laboratories, 1982; Perkin-Elmer, 1985) and an analytical one determined during the analysis, were used in this study and are presented in Appendix I through L. The analytical detection limit was determined by analyzing a blank sample

multiple times and then calculating the standard deviation. The result of detection limit is triple the calculated standard deviation (Metacalfe, 1987). The precision of the analytical data was determined by tripling the standard deviation of analytical data.

2.5 Data Analysis

The results of engineering property tests were presented as tables and graphs showing the relationships between the proportions of shredded tire in the soil-tire mixtures and the various engineering properties of the mixtures (density, permeability, compressive strength, etc.). The graphs were used to determine:

- a) the optimum proportion of shredded tire material for each soil type that yields the best compromise of desired engineering properties,
- b) the optimum size range of shredded tire material that yields the best combination of desired engineering properties for each soil type, and
- c) the optimum properties of soil-tire mixtures that could be used for design purposes.

The information relating to the construction of the test embankment was used to suggest practical applications of tire stabilized soils. The construction methods and construction equipment were evaluated during the construction stage of the test embankment. The survey data representing the settlement of the crest of the embankment and slope angles versus time were presented as graphs to judge the suitability of soil-tire mixtures in building embankments.

The results of chemical analyses were used to evaluate the environmental impact of

the use of tire-stabilized soils in highway construction. The criteria set in EPA's Federal Register 57 (EPA, 1992) were used for this purpose.

CHAPTER 3

ENGINEERING PROPERTIES OF SOILS, SHREDDED TIRE CHIPS, AND SOIL-TIRE MIXTURES

3.1 Engineering Properties of Soils Used

Engineering tests were performed to determine plasticity characteristics, moisture-density relations, permeability, unconfined compressive strength, shear strength parameters (friction and cohesion), and compressibility for the two soil types used in this study. The results are presented in Table 3.1. Based on Atterberg limits, and using the Unified Soil Classification System (USCS), the silt was classified as a nonplastic silt (ML) and the clay as a low plasticity clay (CL).

3.2 Engineering Properties of Shredded Tire Material Used

Three different size ranges of shredded scrap tire (1/4"-1/2" or 7 mm-13 mm; 1/2"-1" or 13 mm -25 mm; and 1"-1 1/2" or 25 mm-38 mm) were used in this study. The dry density and permeability values were determined for all three sizes and are listed in the Table 3.2. The properties of the three size ranges of tire chips are obviously not different from each other.

3.3 Engineering Properties of Soil-Tire Mixtures

3.3.1 Moisture-Density Relationships

The results of compaction tests for both soil types, three different size ranges of

Table 3.1: Engineering properties of the soils used.

Physical Properties	Soil Used	
	Silt	Clay
Liquid Limit (LL)	26.9	31.5
Plasticity Limit (PL)	24.2	20.3
Plasticity Index (PI)	2.7	11.2
Optimum Water Content (%)	15.7	16.8
Maximum Dry Density (pcf)	106.8	102.5
Permeability (cm/sec)	4.48E-07	4.32E-08
Unconfined Compressive Strength (psf)	4077	6600
Soil Classification (USCS)	ML	CL

Table 3.2: Dry density and permeability of shredded tire material.

Physical Properties	Shredded Tire Size		
	1/4"-1/2"	1/2"-1"	1"-1 1/2"
Dry Density (pcf)	43.2	43.5	43.6
Permeability (cm/sec)	0.16	0.18	0.18

shredded tire material, and soil-tire mixtures are presented in Appendix A. The peak points of the curves included in Appendix A were chosen to represent the maximum dry density and optimum water content values. The relationships of maximum dry density versus shredded tire content for silt-tire and clay-tire mixtures are presented in Figures 3.1 and 3.2, respectively. The figures show that the maximum dry density of the mixtures decreases with increasing shredded tire content for both soil types and all three tire size, and that linear equations can be used to fit the data. The trends are similar for all three tire sizes in both types of soil-tire mixtures, with clay-tire mixtures exhibiting lower rates of decreasing density than silt-tire mixtures. For silt-tire mixtures, the maximum dry density decreases from 107 pcf (1.70 Mg/m^3) for pure silt to nearly 53 pcf (0.85 Mg/m^3) at 90% shredded tire content for all three sizes of tire chips whereas for clay-tire mixtures, the maximum dry density decreases from 103 pcf (1.65 Mg/m^3) for pure clay to 55 pcf (0.88 Mg/m^3) at 90% shredded tire content for all three sizes of tire chips. For both soil-tire mixtures, the maximum dry density values are reduced to 2/3 of the values for pure soils at approximately 50% tire content, indicating that a lightweight fill material can be provided by mixing 50% soil with 50% shredded tire material by weight.

The relationships between optimum water content and shredded tire content for silt-tire mixtures are shown in Figure 3.3, while Figure 3.4 shows the same relationships for clay-tire mixtures. The figures show that the optimum water contents of the mixtures decrease with increase of shredded tire content, the decrease being gradual up to 60% tire content. Below 60% tire content, the optimum water contents of the mixtures are around 15%. When the shredded tire content is more than 60%, the optimum water content

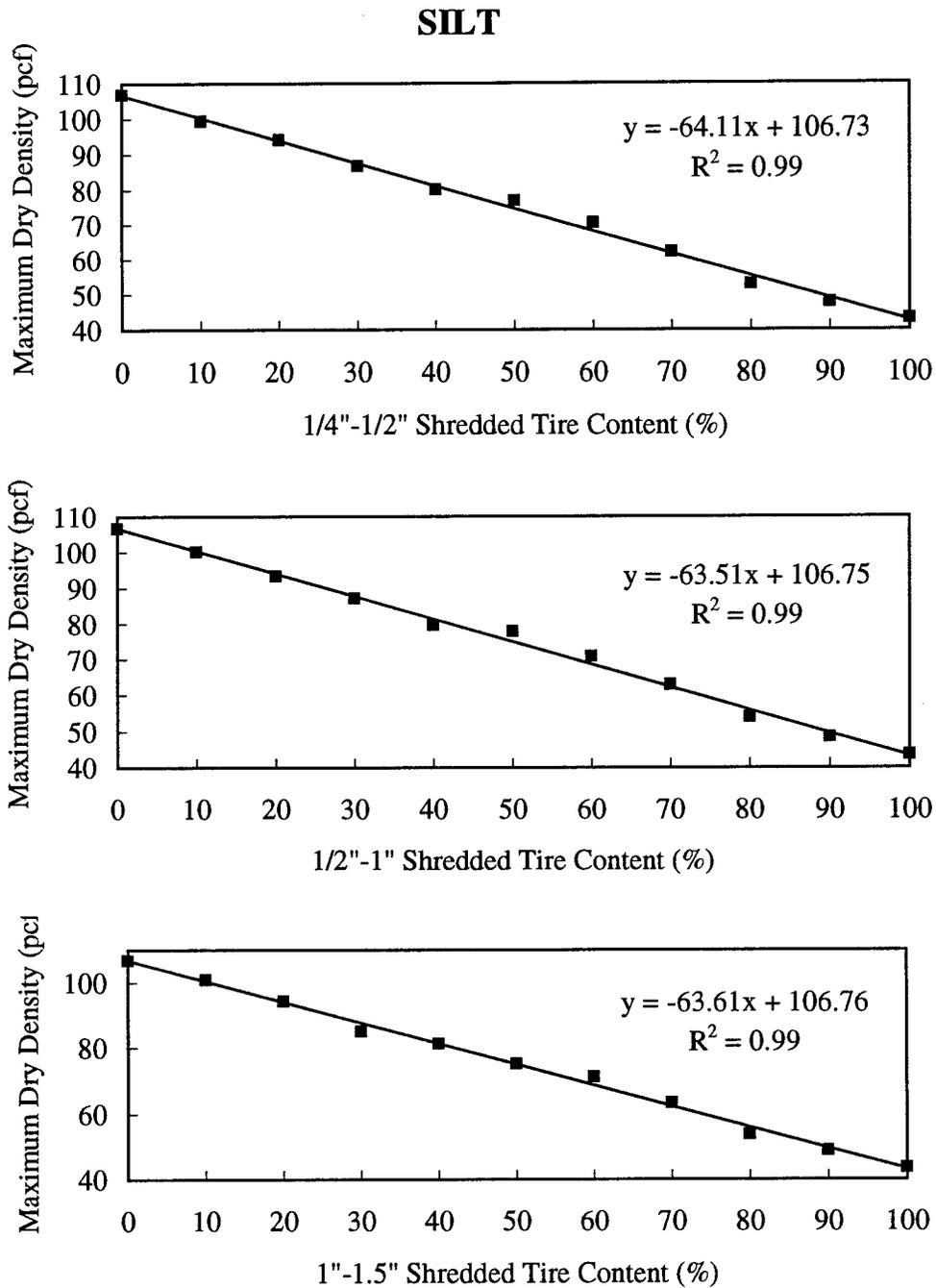


Figure 3.1 Maximum dry density versus shredded tire content for silt-tire mixtures.

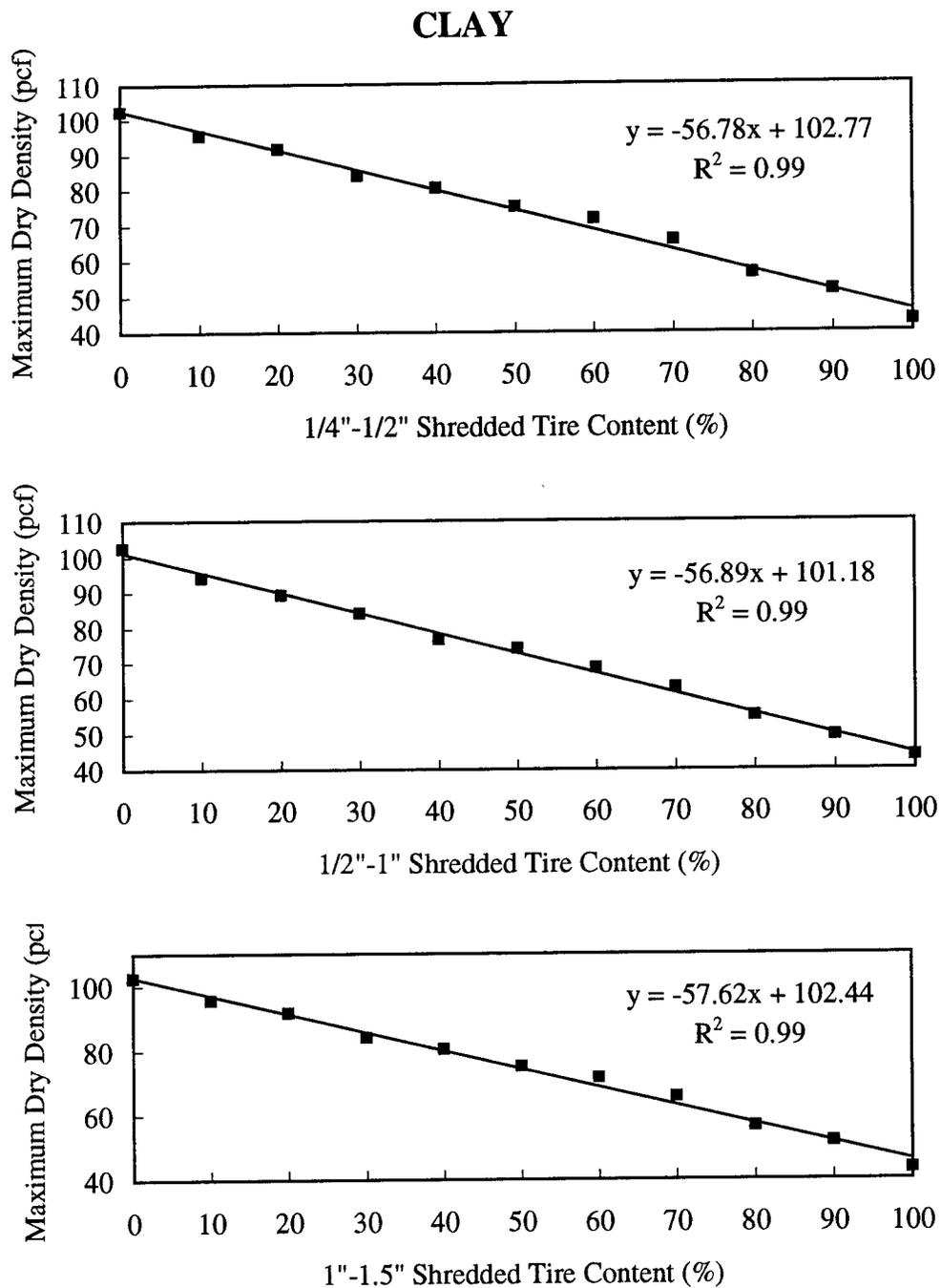


Figure 3.2 Maximum dry density versus shredded tire content for clay-tire mixtures.

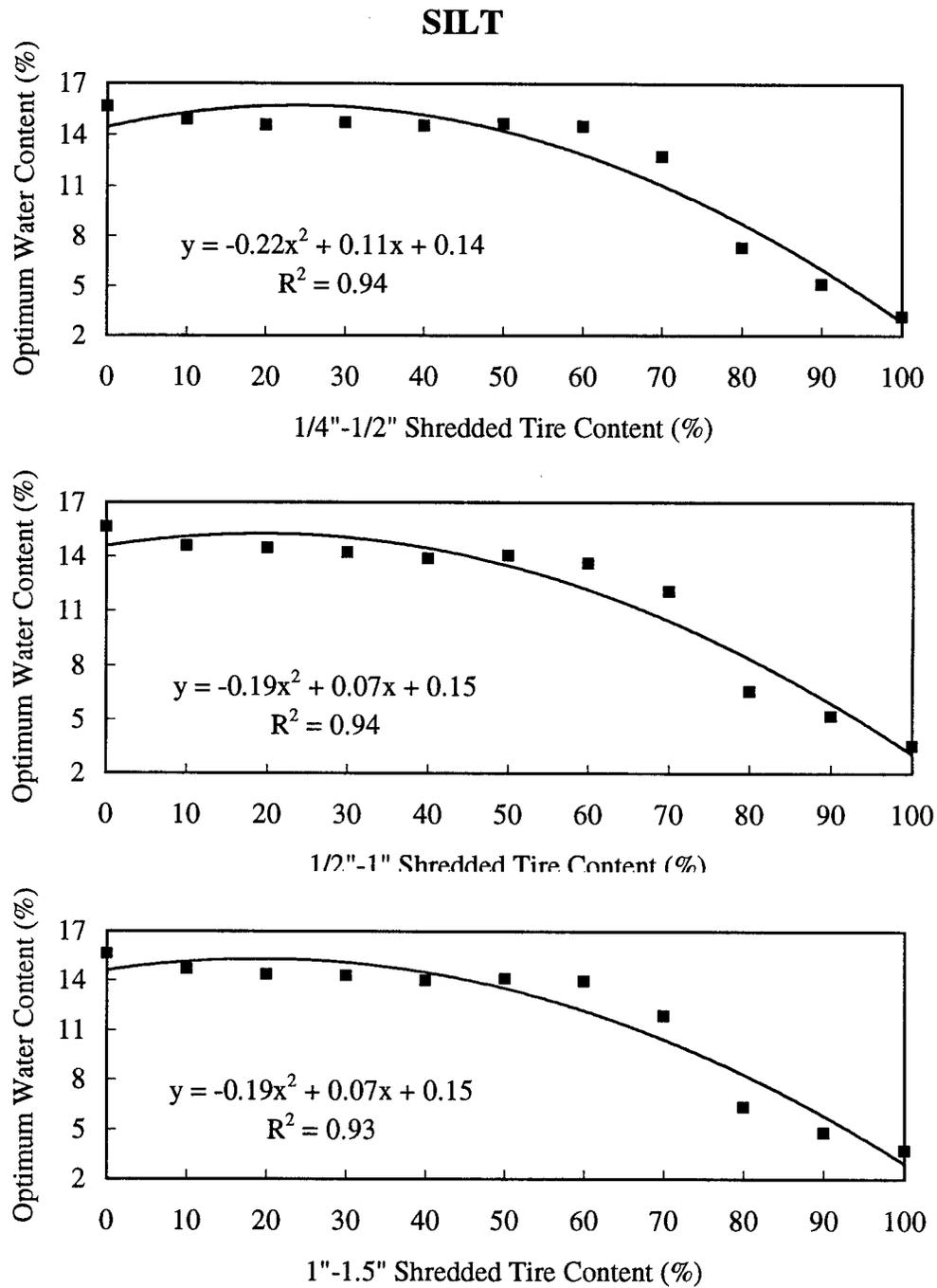


Figure 3.3 Optimum water content versus shredded tire content for silt-tire mixtures.

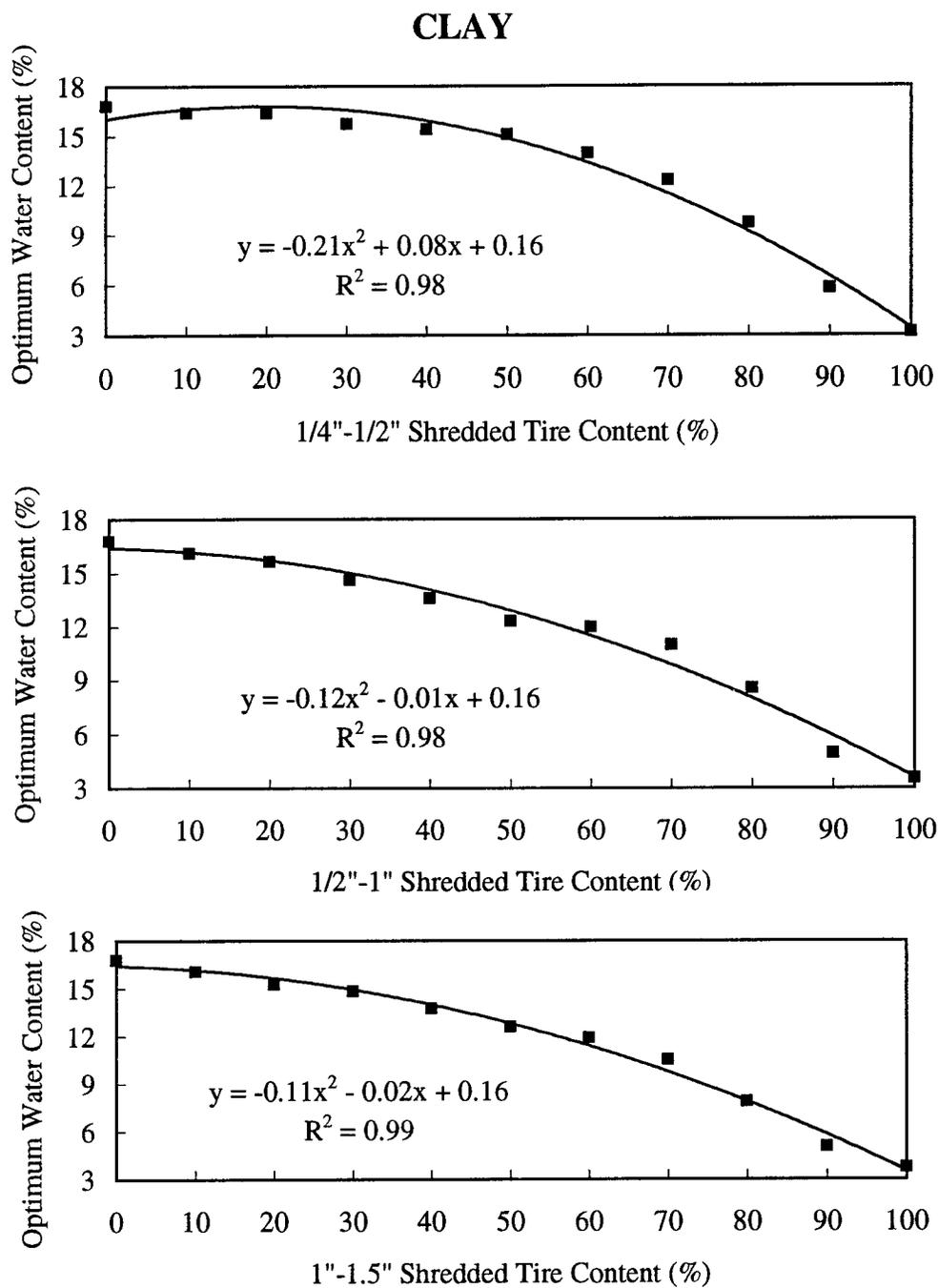


Figure 3.4 Optimum water content versus shredded tire content for clay-tire mixtures.

decreases dramatically from 15% to 3% with increase of shredded tire content.

In order to find an equation to describe the relationship between optimum water content and shredded tire content, the F-statistic test was adopted to determine the polynomial degree which provides the best fit to the data. The F-statistic tests whether the equation provides a good fit to the data. A larger F value supports the use of the regression line, while a small value suggests that independent variable is of little use in explaining the variation in the dependent variable. The F values for silt-tire mixtures with polynomial degrees of 1, 2, and 3 are listed in Table 3.3 and for clay-tire mixtures in Table 3.4. For both soils and all three tire chip sizes, the F value is the highest when the polynomial degree is 2. Therefore, an equation with degree 2 was used to fit the optimum water content data corresponding to 0% (pure soil) to 100% (pure tire chips) shredded tire content. The fitting lines, equations, and correlation coefficient values for silt-tire mixtures are shown in Figure 3.3 and for clay-tire mixtures in Figure 3.4.

Since the optimum water content versus shredded tire content data follow two distinctly different slopes, the data points were separated into two groups. Data points falling on a gentler slope were considered as the first group and those falling on a steeper slope as the second group. Of interest was to determine where a break point, referred to as the critical point in the discussion below, between these two groups of data exists so that linear equations could be developed for each group. To accomplish this, R^2 values were determined for different subsets of data (0-50%, 50-100%, 60-100%, etc.) as shown in Tables 3.5 and 3.6. The subset which had the highest R^2 value in the second column of the table was taken as the first group of data and the highest value of shredded tire content

Table 3.3: F values for silt-tire mixtures containing different tire sizes, with different polynomial degrees.

Silt-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2	Polynomial Degree = 3
1/4"-1/2" Tire Chips	23.85	58.87	44.44
1/2"-1" Tire Chips	31.00	57.90	38.81
1"-1.5" Tire Chips	29.86	51.05	32.11

Table 3.4: F values for clay-tire mixtures containing different tire sizes, with different polynomial degrees.

Clay-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2	Polynomial Degree = 3
1/4"-1/2" Tire Chips	39.47	239.13	203.37
1/2"-1" Tire Chips	106.11	209.46	177.91
1"-1.5" Tire Chips	126.86	405.64	293.81

Table 3.5: R^2 values of different subsets of optimum water content versus shredded tire content data for silt-tire mixtures.

(a) 1/4"-1/2" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.60	0.93	0.96
Subset	0-60	60-100	70-100
R^2	0.61	0.96	0.93
Subset	0-70	70-100	80-100
R^2	0.65	0.93	0.99

(b) 1/2"-1" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.78	0.93	0.94
Subset	0-60	60-100	70-100
R^2	0.82	0.94	0.88
Subset	0-70	70-100	80-100
R^2	0.83	0.88	0.99

(c) 1"-1.5" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.74	0.93	0.93
Subset	0-60	60-100	70-100
R^2	0.76	0.93	0.86
Subset	0-70	70-100	80-100
R^2	0.74	0.86	0.99

Table 3.6: R^2 values of different subsets of optimum water content versus shredded tire content data for clay-tire mixtures.

(a) 1/4"-1/2" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.96	0.96	0.98
Subset	0-60	60-100	70-100
R^2	0.92	0.98	0.99
Subset	0-70	70-100	80-100
R^2	0.87	0.99	0.98

(b) 1/2"-1" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.97	0.93	0.96
Subset	0-60	60-100	70-100
R^2	0.98	0.96	0.97
Subset	0-70	70-100	80-100
R^2	0.99	0.97	0.93

(c) 1"-1.5" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-50	50-100	60-100
R^2	0.94	0.96	0.98
Subset	0-60	60-100	70-100
R^2	0.97	0.98	0.97
Subset	0-70	70-100	80-100
R^2	0.98	0.97	0.95

in the subset containing that highest R^2 value was defined as the critical point. The subset which had the highest R^2 value in the last two columns of the table and that corresponded to the subset already selected as group one was then chosen as the second group. For example, in Table 3.5 (a), 0-70% shredded tire content showing the highest R^2 value in the second column was selected as the first group of data and 70% of shredded tire content was defined as the critical point whereas 80-100% tire content, in the third column of the table, was selected as the second group because of its higher R^2 value (0.99) than 70-100% tire content ($R^2 = 0.93$). The soil-tire mixtures behave more like a soil when the proportion of shredded tire material is less than the critical point. Once the critical points were determined from the R^2 values listed in Tables 3.5 and 3.6, the best fit lines and their equations were established. These are shown in Figures 3.5 and 3.6 for silt-tire mixtures and clay-tire mixtures, respectively. If a gap exists between two regression lines, the critical point is not shared by two groups. If no gap exists between the two regression lines, the critical point is shared by the two groups. Figure 3.5 shows that the biggest tire chips size (1"-1.5" or 25 mm-38 mm) has a smaller value of critical point. This is because the bigger tire chips size occupies more space than smaller tire chips size for the same proportion of shredded tire material, by weight. The 1"-1.5" (25 mm-38 mm) size tire chips hit the critical point earlier than other two smaller tire chips sizes in the silt-tire mixtures. However, the clay-tire mixtures show that a lower proportion of shredded tire material is required to achieve the critical point for the smaller size tire chips (Figure 3.6). As the clay soil is more cohesive and lumpy, the smaller size of tire chips tends to be

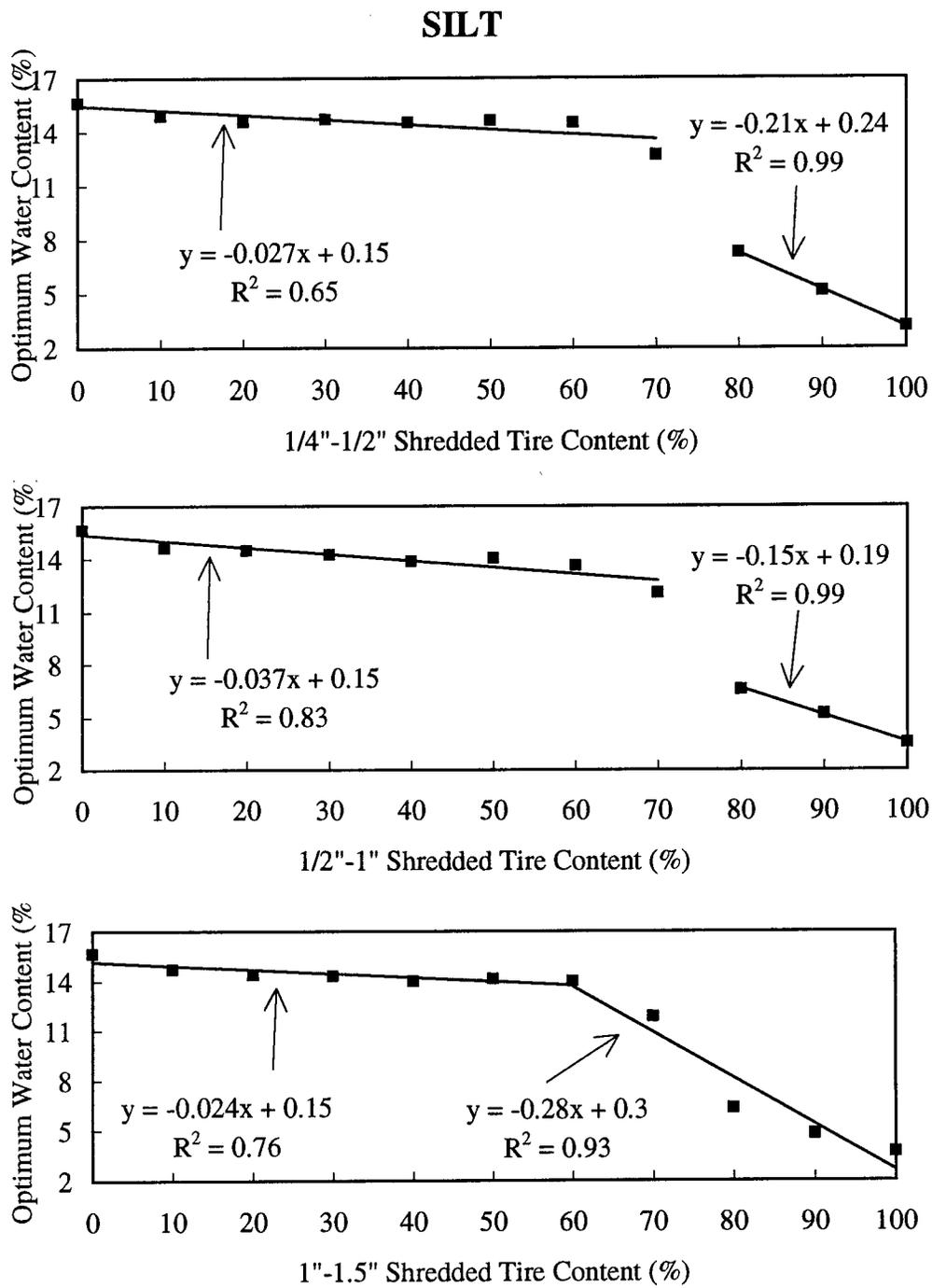


Figure 3.5 Optimum water content versus shredded tire content for silt-tire mixtures.

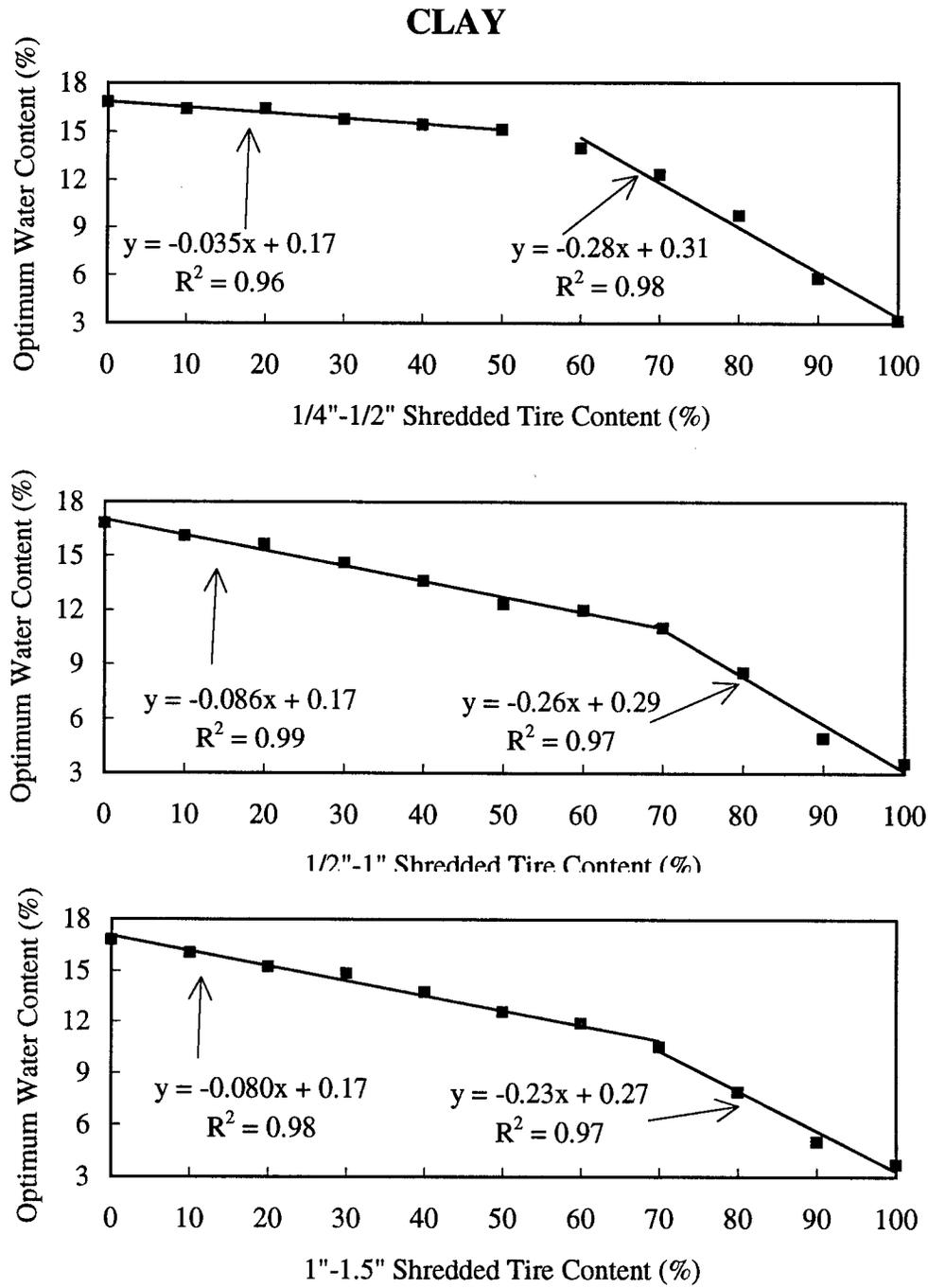


Figure 3.6 Optimum water content versus shredded tire content for clay-tire mixtures.

distributed more evenly than the bigger sizes of tire chip and, therefore, lesser proportion of shredded tire material is required beyond the critical point in case of smaller size tire chips.

The slopes of the linear regression lines represent the decreasing rates of optimum water content with shredded tire content. In both silt-tire and clay-tire mixtures, the decreasing rates of optimum water content are similar for all three tire chip sizes. A comparison of silt-tire and clay-tire mixtures, containing the same size of shredded tire material, shows that the rate of decrease of optimum water content is less for the silt-tire mixtures than for the clay-tire mixtures when the shredded tire content is less than the critical point but the rates of decrease of optimum water content are similar for both soil-tire mixtures when the shredded tire content is more than the critical point.

3.3.2 Permeability

The results of individual permeability tests are presented in Appendix B. The results for pure soils and soil-tire mixtures were plotted on the semilogarithmic paper and presented in Figures 3.7 and 3.8 for silt-tire mixtures and in Figures 3.9 and 3.10 for clay-tire mixtures. The plots (Figure 3.7 and Figure 3.9) show that permeability of the mixtures increases with increase of shredded tire content. The permeability increases dramatically from 2×10^{-6} in/min (10^{-7} cm/sec) to 2 in/min (0.1 cm/sec) for silt-tire mixtures and from 2×10^{-7} in/min (10^{-8} cm/sec) to 2 in/min (0.1 cm/sec) for clay-tire mixtures when the increase in shredded tire content approaches 40%. When the shredded tire content is more than 40%, the permeability values are relatively close and increase only gradually with

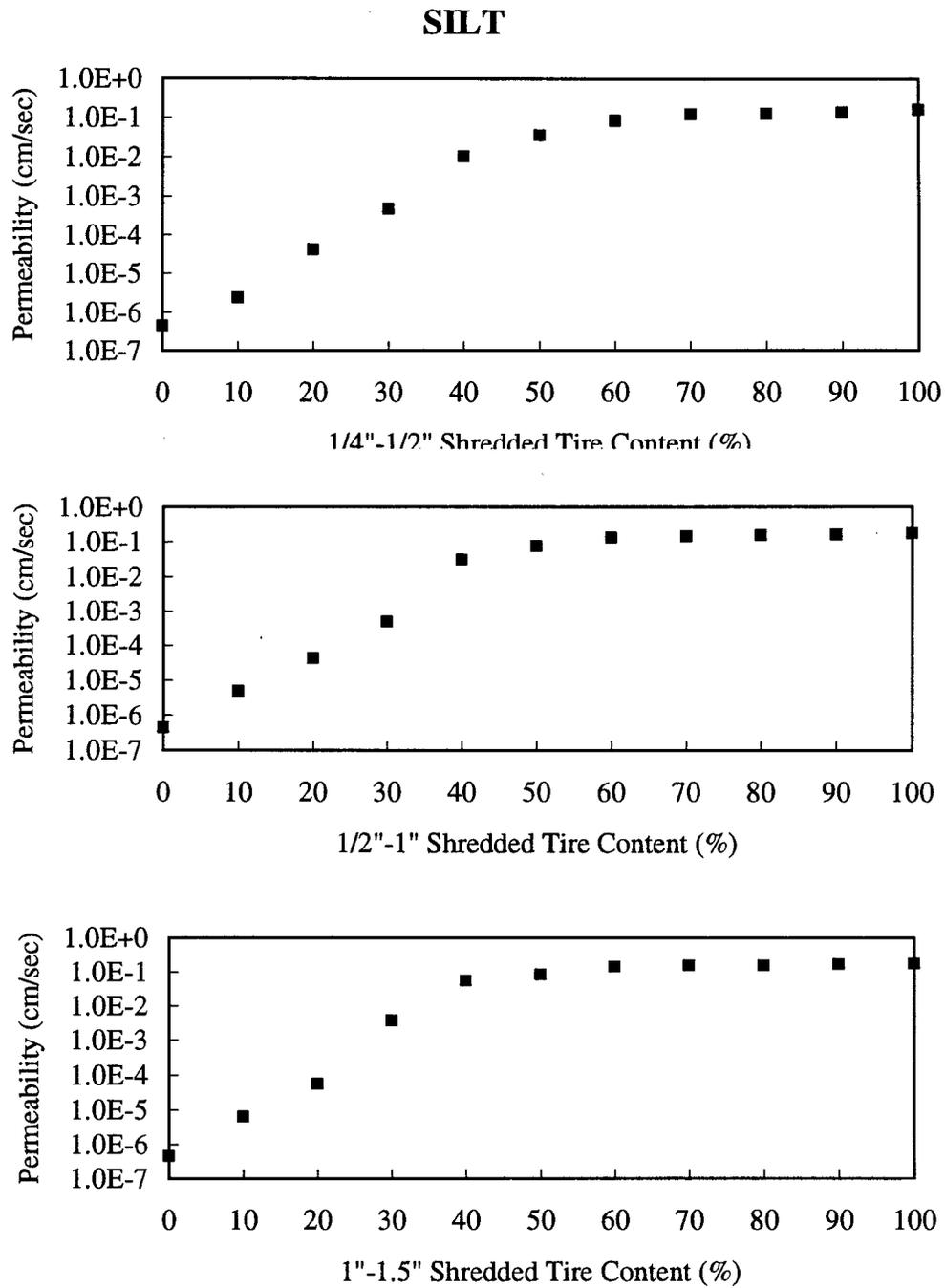


Figure 3.7 Permeability versus shredded tire content for silt-tire mixtures.

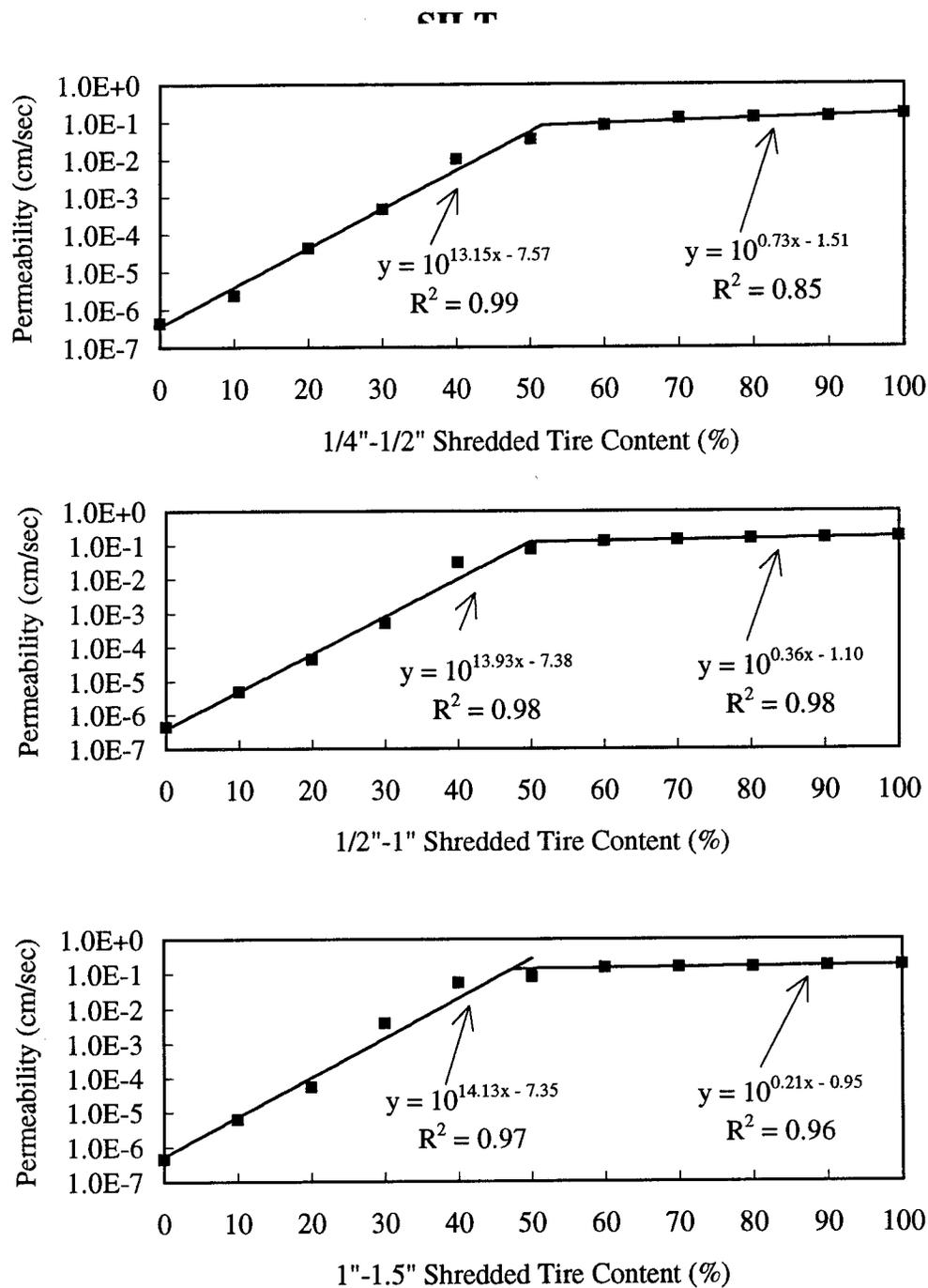


Figure 3.8 Results of linear regression analysis for permeability versus shredded tire content for silt-tire mixtures.

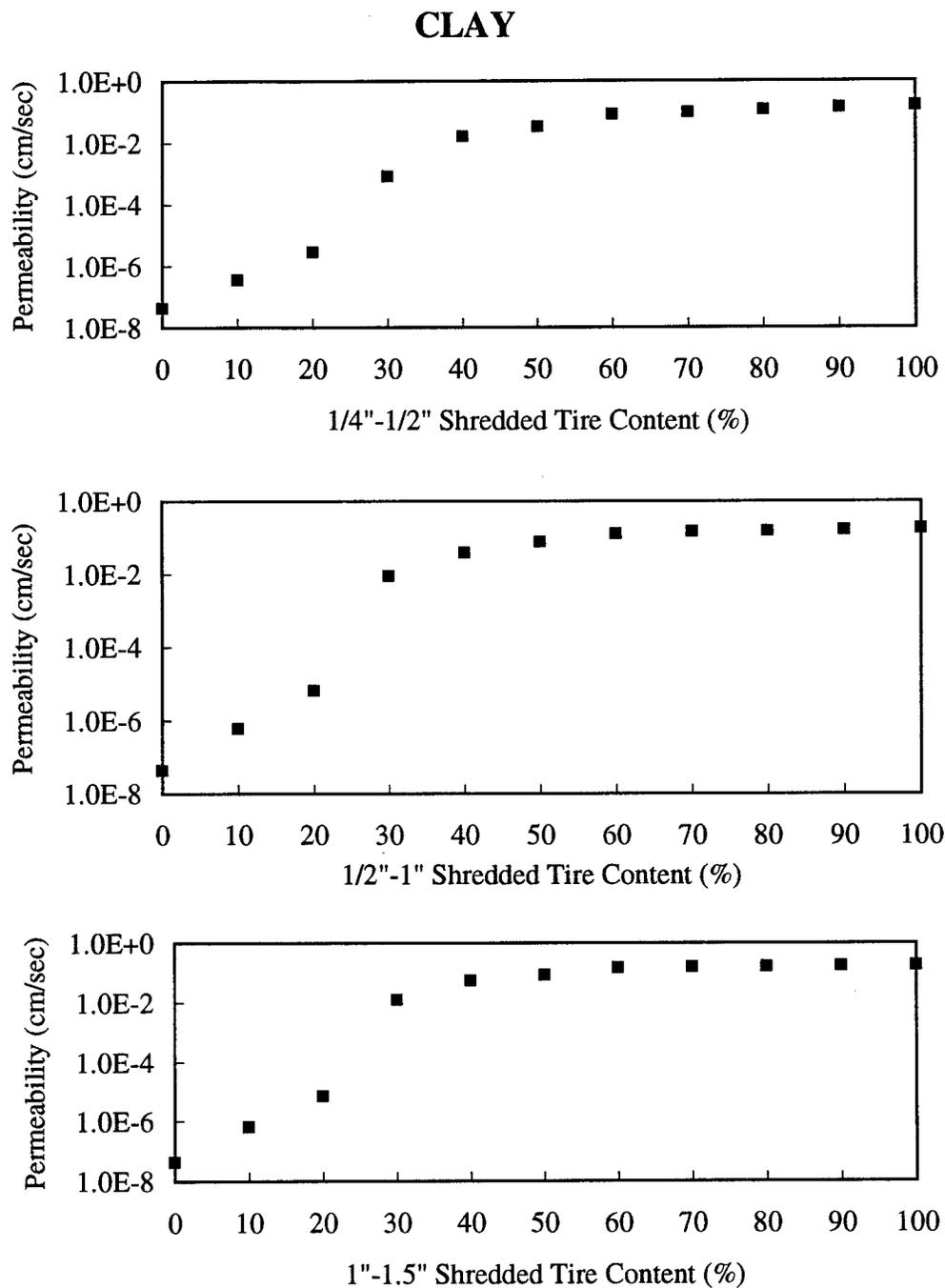


Figure 3.9 Permeability versus shredded tire content for clay-tire mixtures.

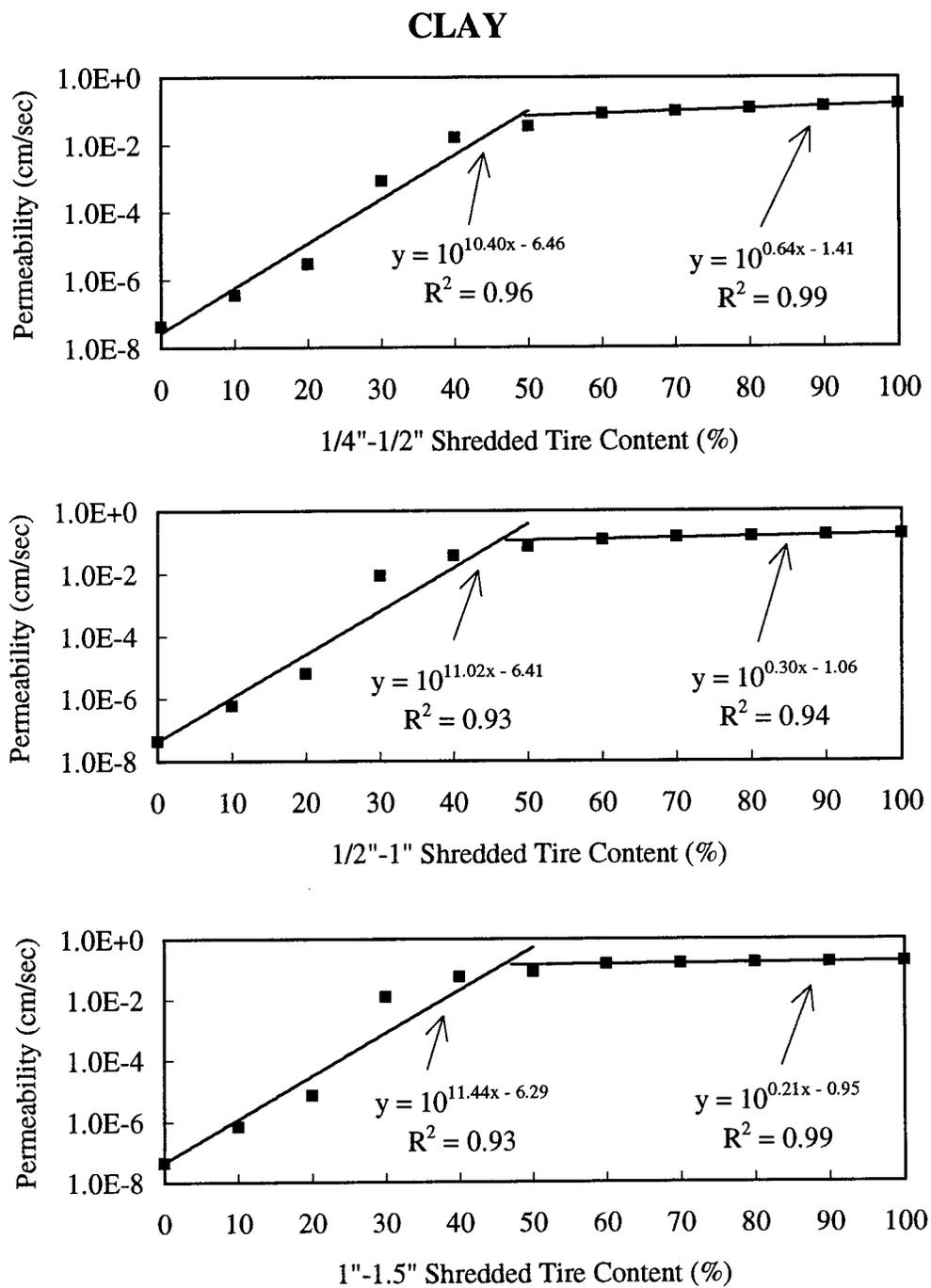


Figure 3.10 Results of linear regression analysis for permeability versus shredded tire content for clay-tire mixtures.

increase of shredded tire content. Between 40% to 100% tire content, the permeability is around 2 in/min (0.1 cm/sec).

The method used to determine the critical point for the optimum water content versus shredded tire content data was also applied to separate the permeability versus shredded tire content data into two groups. The R^2 values for different subsets of data are shown in Tables 3.7 and 3.8, whereas Figures 3.8 and 3.10 show the by exponential equations for the best fit lines as well as the correlation coefficient values. The plots in Figures 3.8 and 3.10 show that the slopes of regression lines are steeper when the shredded tire content is less than 50% than when the shredded tire content is more than 50% for both soils and all three tire sizes. When the shredded tire content is less than 50%, the rates of permeability increase are similar for both soil-tire mixtures and all three tire sizes. When the shredded tire content is more than 50%, the permeability of mixture with smaller tire chips increases rather more than that with bigger tire chips for both soil-tire mixtures. Comparison of silt-tire mixtures with clay-tire mixtures shows that the rate of increase of permeability is less in case of silt-tire mixtures than in case of clay-tire mixtures when the shredded tire content is more than 40%. When the shredded tire content is less than 50%, however, the rates of increase are similar for both types of soil-tire mixtures. The permeability behavior of soil-tire mixtures appears to be controlled by the soil when the proportion of shredded tire is less than 50%. The mixtures behave as an aggregate material if the proportion of shredded tire material is more than 50%.

3.3.3 Strength Characteristics

Table 3.7: R^2 values of different subsets of permeability versus shredded tire content data for silt-tire mixtures.

(a) 1/4"-1/2" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.99	0.77	0.76
Subset	0-50	50-100	60-100
R^2	0.99	0.76	0.85

(b) 1/2"-1" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.98	0.72	0.74
Subset	0-50	50-100	60-100
R^2	0.98	0.74	0.98

(c) 1"-1.5" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.98	0.76	0.66
Subset	0-50	50-100	60-100
R^2	0.97	0.66	0.96

Table 3.8: R^2 values of different subsets of permeability versus shredded tire content data for clay-tire mixtures.

(a) 1/4"-1/2" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.96	0.85	0.84
Subset	0-50	50-100	60-100
R^2	0.96	0.84	0.99

(b) 1/2"-1" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.95	0.78	0.79
Subset	0-50	50-100	60-100
R^2	0.93	0.79	0.94

(c) 1"-1.5" Tire Chips

Subset / R^2	Shredded Tire Content (%)		
Subset	0-40	40-100	50-100
R^2	0.95	0.76	0.66
Subset	0-50	50-100	60-100
R^2	0.93	0.66	0.99

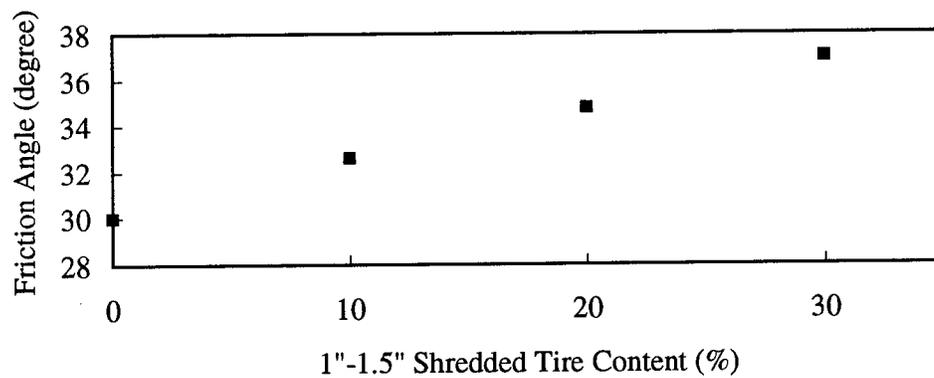
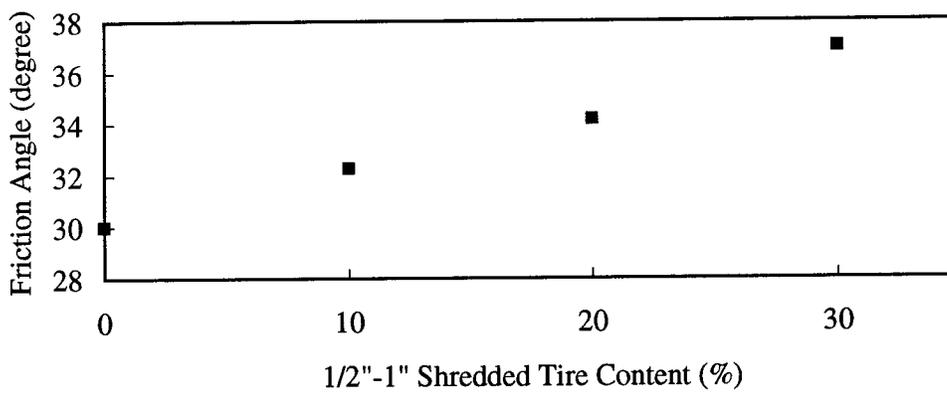
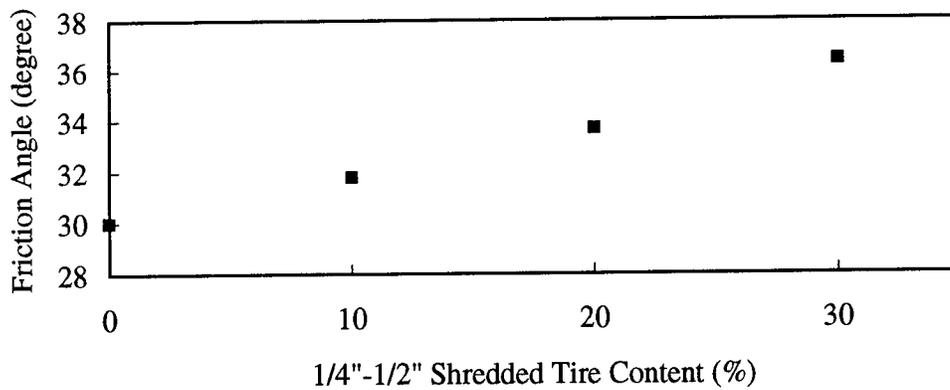
SILT

Figure 3.11 Friction angle versus shredded tire content for silt-tire mixtures.

The strength characteristics of soil-tire mixtures were determined by performing the unconfined compression and the triaxial tests. The triaxial test was used to define the friction angle and cohesion values for both types of soil-tire mixtures. The results of individual triaxial tests are shown in Appendix C.

Friction Angle and Cohesion Parameters

The friction angle (ϕ) and cohesion (c) values for silt-tire and clay-tire mixtures, containing 10% to 30% shredded tire by weight, were measured on samples compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. The results are presented in Figures 3.11 through 3.14. The plots of friction angle versus shredded tire content for silt-tire mixtures are presented in Figure 3.11 and those for clay-tire mixtures in Figure 3.12. The plots show that the friction angle of the mixtures increases with increasing shredded tire content for all three tire chip sizes when the shredded tire content is less than 30%. For clay-tire mixtures, however, the friction angle increases up to 20% shredded tire content and then decreases for all three tire chip sizes. When the proportion of shredded tire material is more than 20% in clay-tire mixtures, the clay-tire mixtures do not compact into a coherent mass and that may have caused a decrease in friction angle at 30% shredded tire content.

The plots of cohesion versus shredded tire content for silt-tire mixtures are presented in Figure 3.13 and for clay-tire mixtures in Figure 3.14. The plots show that the cohesion of the mixtures decreases with increasing tire content for 1/4"-1/2" (7 mm-13 mm) size tire chips for both types of soil-tire mixtures. For the other two tire chip sizes, however, the cohesion values of the mixtures with 10% shredded tire content are almost twice the

CLAY

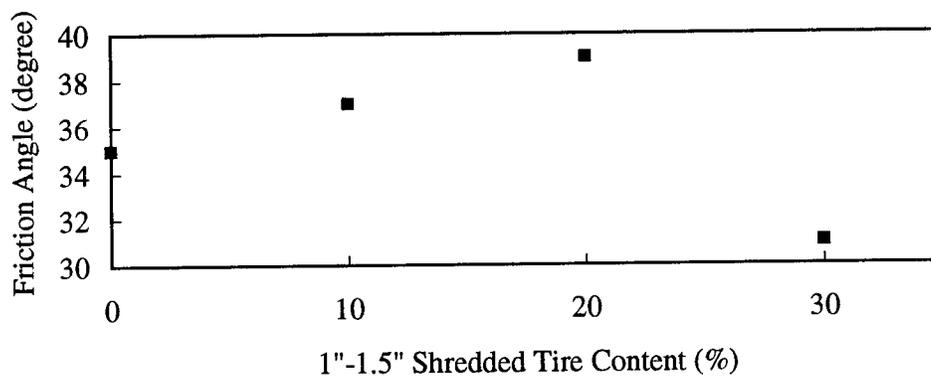
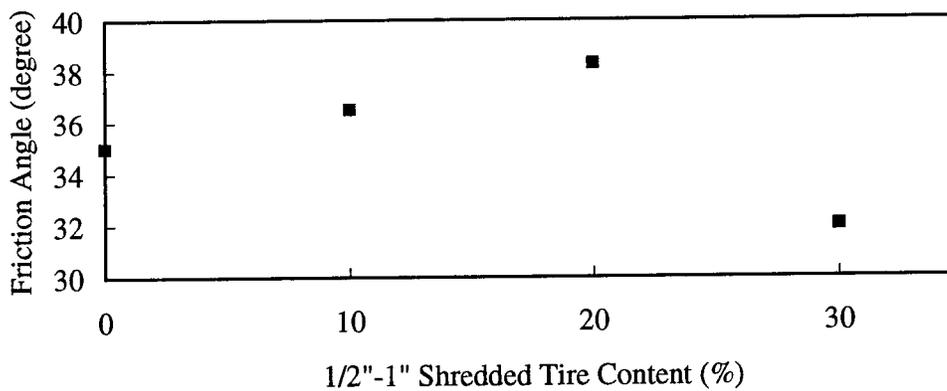
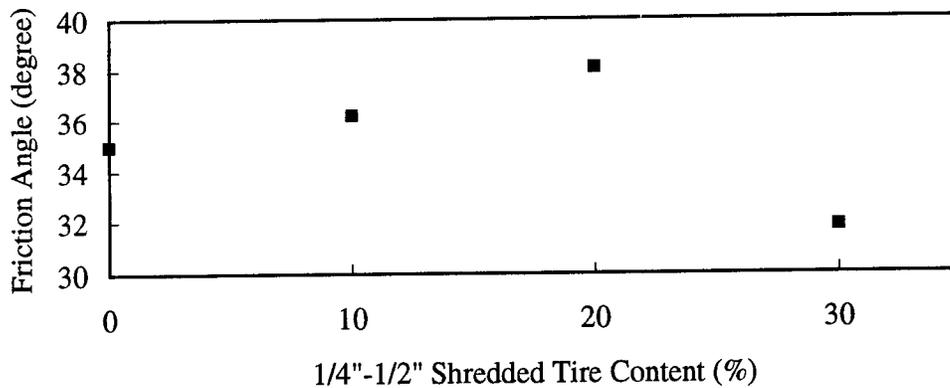


Figure 3.12 Friction angle versus shredded tire content for clay-tire mixtures.

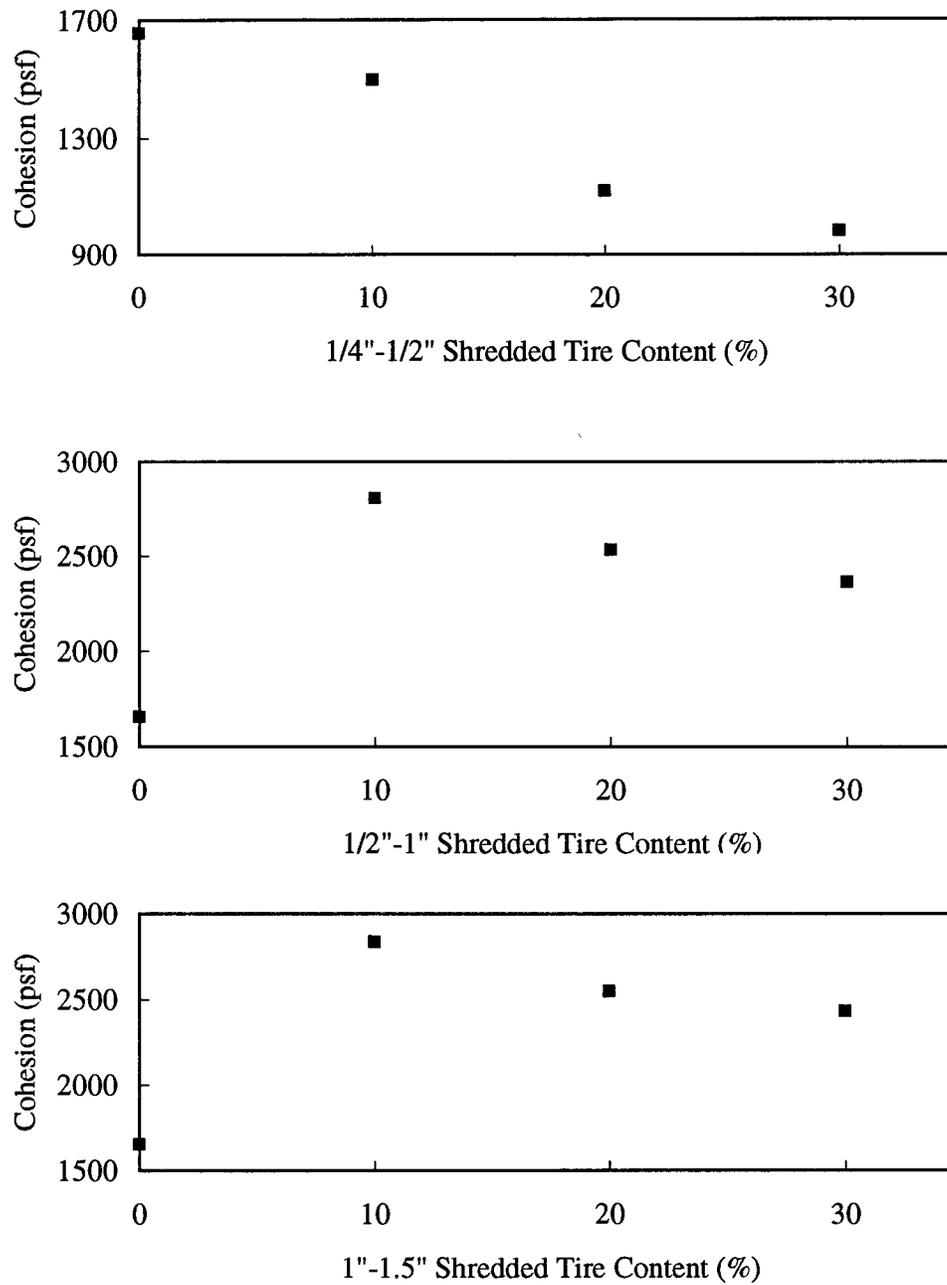
SILT

Figure 3.13 Cohesion versus shredded tire content for silt-tire mixtures.

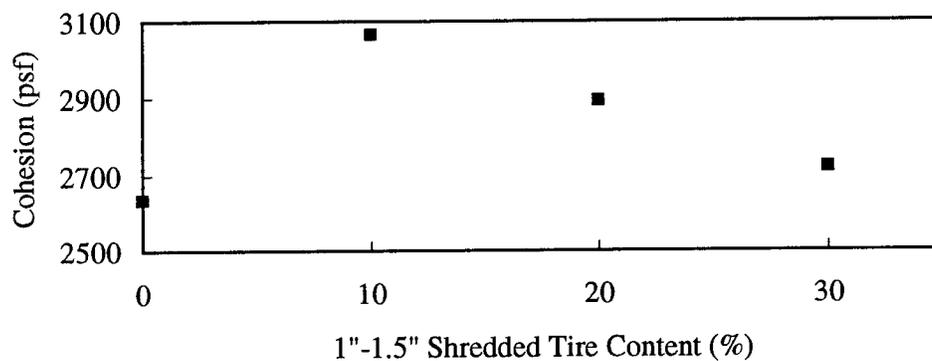
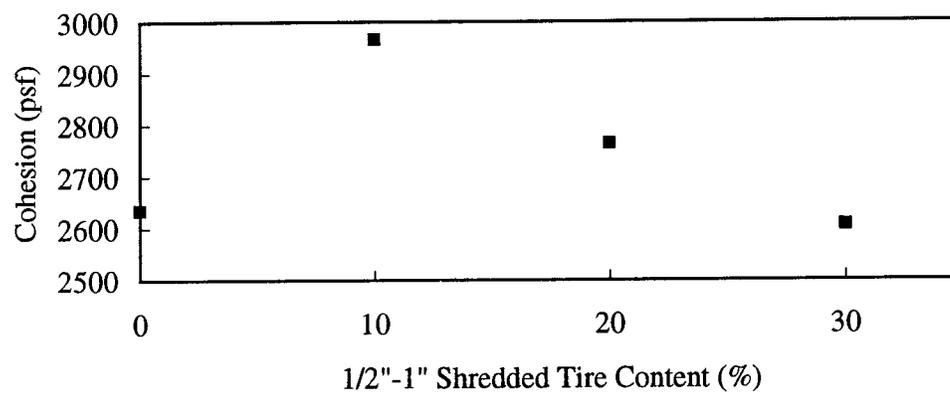
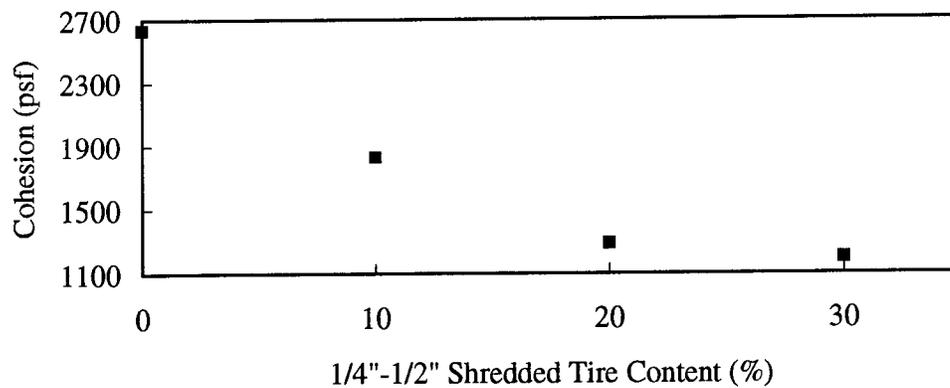
CLAY

Figure 3.14 Cohesion versus shredded tire content for clay-tire mixtures.

cohesion values for pure soils and then decrease slowly for shredded tire content from 10% to 30%. The increase of cohesion in case of two bigger tire chip sizes could be due to use of additional rubber membrane around the sample as described in Chapter 2.

Shear Strength

Shear Strength (τ) was determined for both soil types and all soil-tire mixtures, using Coulomb's equation, given below:

$$\tau = c + \sigma \tan \phi$$

where τ = shear strength (psf)

σ = normal strength (psf)

ϕ = friction angle (degree)

c = cohesion (psf)

Normal stress (σ) was assumed to be 1000 psf (47.9 KN/m²) for calculation purposes. Since the equation takes into account both cohesion and friction angle, it gives a better indication of the overall strength of the soil-tire mixtures. The plots of shear strength versus shredded tire content for silt-tire mixtures are presented in Figure 3.15 and for clay-tire mixtures in Figure 3.16. The plots show that the shear strength of mixtures decreases with increasing tire content for 1/4"-1/2" (7 mm-13 mm) size tire chips in both mixtures. For the other two sizes, the shear strength of the mixtures with 10% shredded tire content increases compared to the pure soils, and then decreases slowly for shredded tire content from 10% to 30%. When the shredded tire content is 30%, the shear strength of silt-tire mixture is higher than the shear strength of pure silt and that of clay-tire mixture

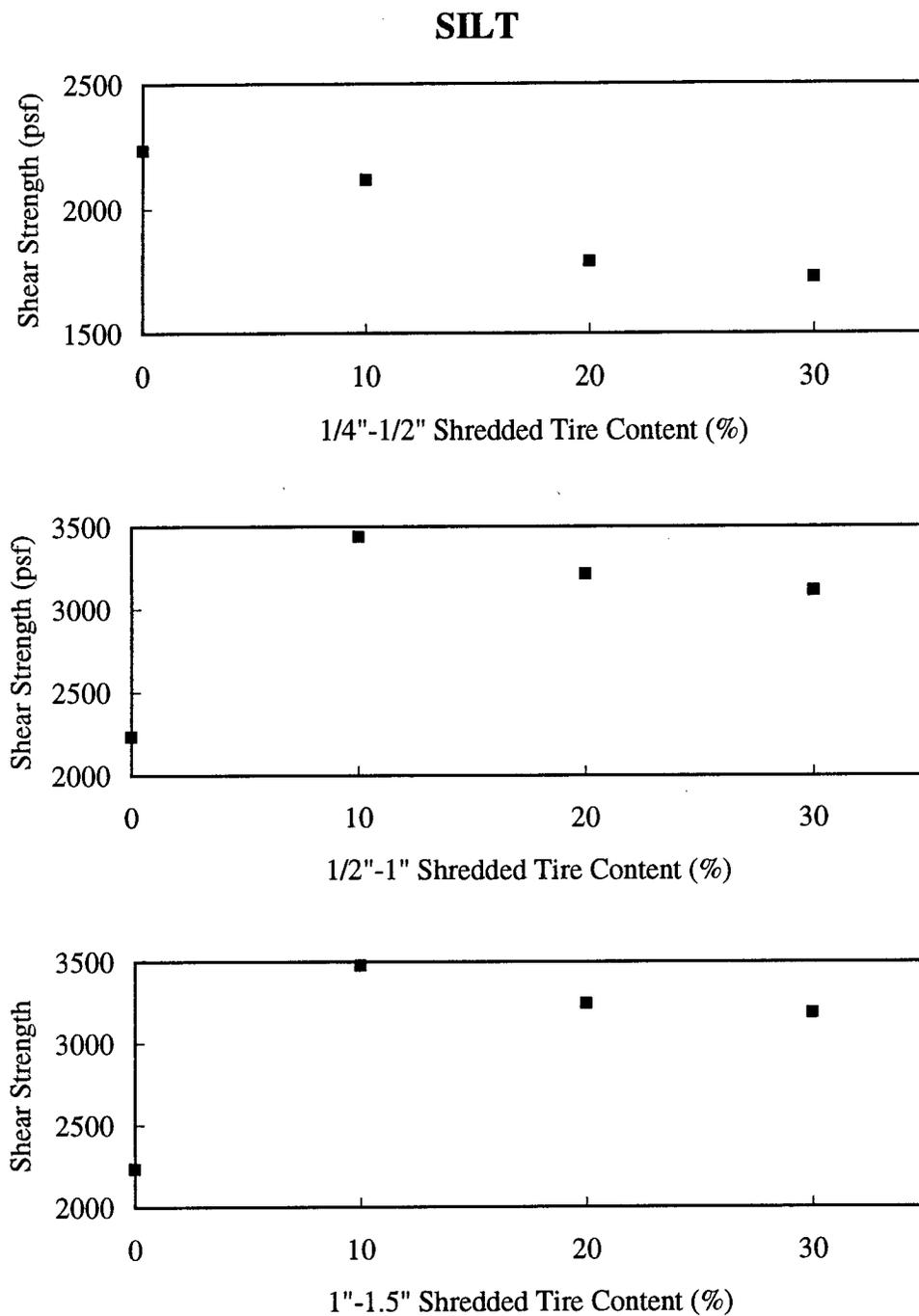


Figure 3.15 Shear strength versus shredded tire content for silt-tire mixtures.

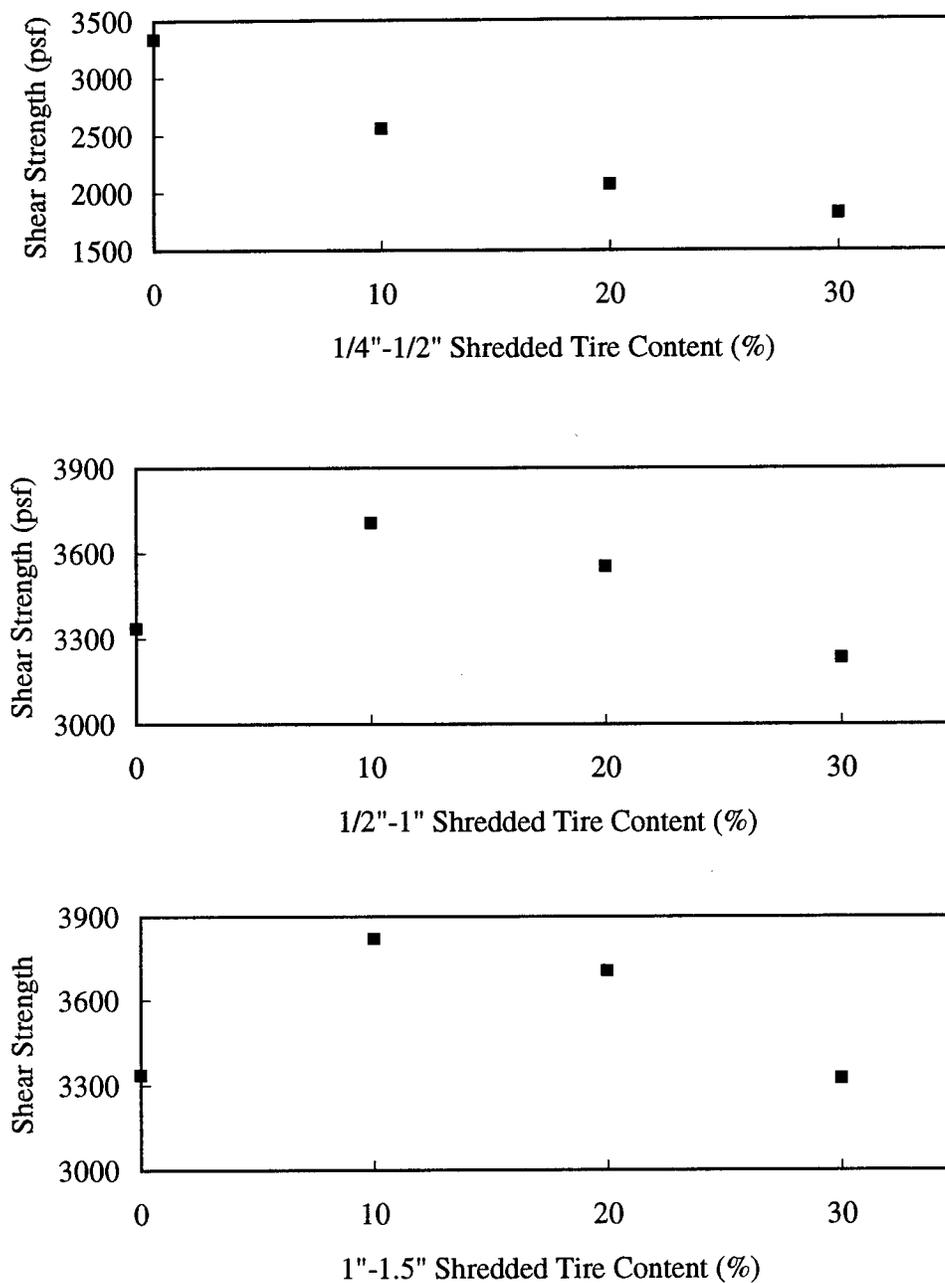
CLAY

Figure 3.16 Shear strength versus shredded tire content for clay-tire mixtures.

is lower than the pure clay for both size ranges of bigger chips. Since the change of cohesion rather than the change of friction angle for each soil-tire mixture, the shear strengths of soil-tire mixtures show the similar trends as the trends of cohesion of soil-tire mixtures.

Unconfined Compressive Strength

The unconfined compressive strength for silt-tire mixtures and clay-tire mixtures was measured on samples compacted to at least 95% of the maximum dry density and within $\pm 2\%$ of the optimum water content. The results of unconfined compression tests are shown in Appendix D. The plots of unconfined compressive strength versus shredded tire content, and the regression lines, for silt-tire mixtures are presented in Figure 3.17 and for clay-tire mixtures in Figure 3.18. The plots show that the unconfined compressive strength of the mixtures decreases with increasing amount of shredded tire material. If the compacted sample of the mixture fell apart before the test was performed, the unconfined compressive strength of that sample was assumed to be zero. Only the compressive strength values higher than zero were chosen to do the data fitting analysis. Based on the F-statistic test (Tables 3.9 and 3.10), the data for silt-tire mixtures were fitted by a linear equation and the data for clay-tire mixtures by an exponential equation. This implies that the unconfined compressive strength decreases gradually with the addition of shredded tire material to silt. For clay-tire mixtures, however, the compressive strength decreases rapidly with the addition of shredded tire material in the beginning, and then more gradually as additional amounts are added. The unconfined compressive strength behavior of silt-tire mixtures and clay-tire mixtures are different because the clay soil is more

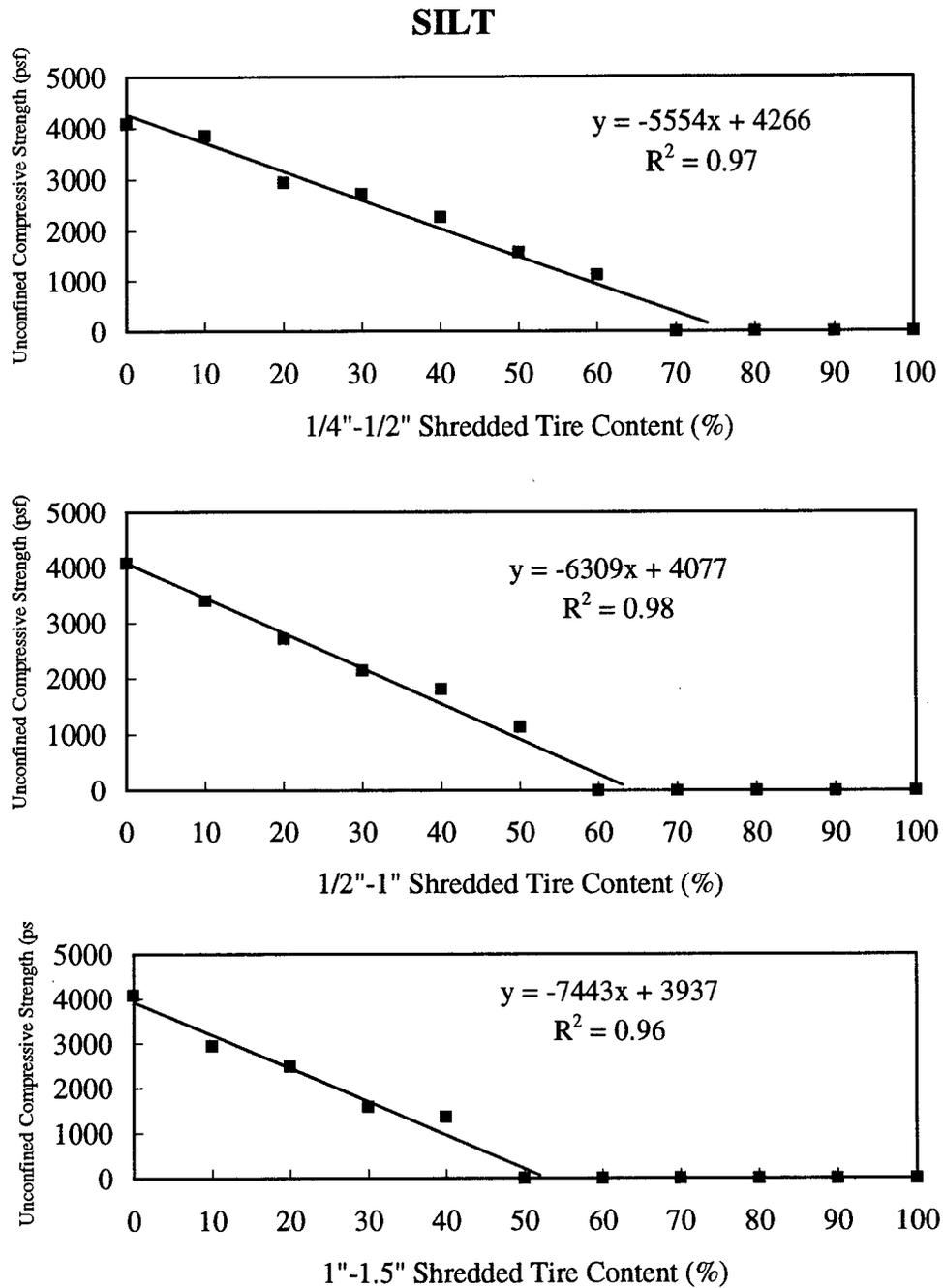


Figure 3.17 Unconfined compressive strength versus shredded tire content for silt-tire mixtures.

CLAY

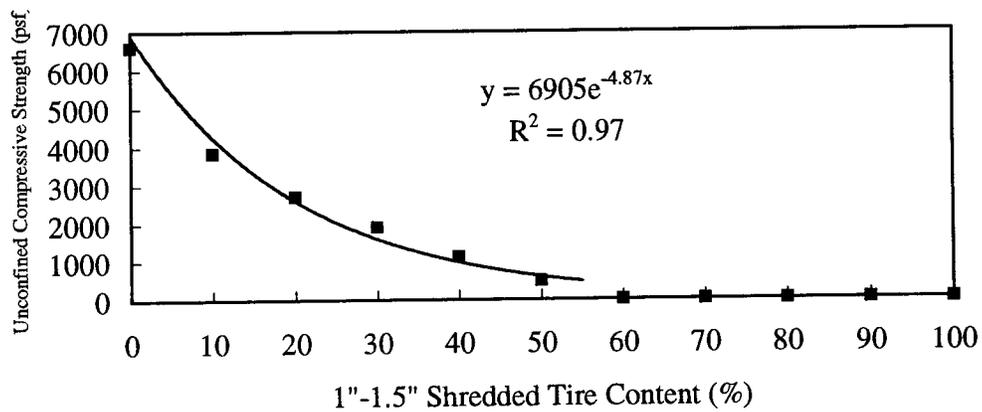
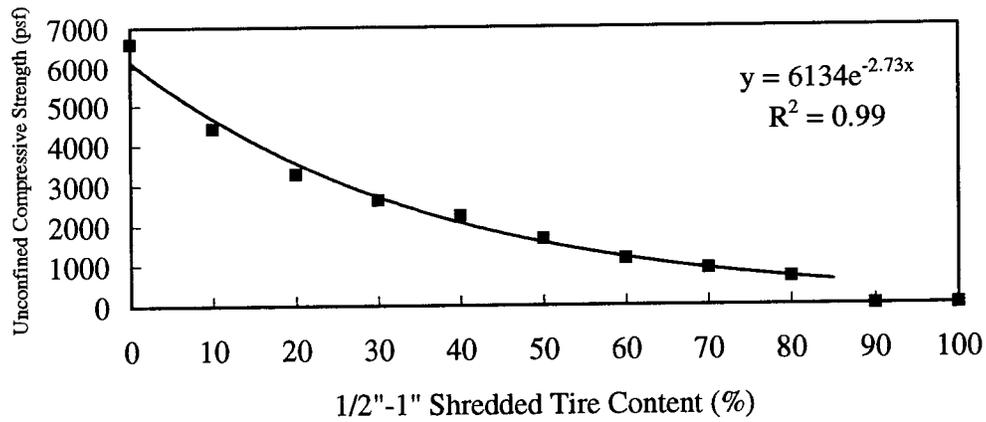
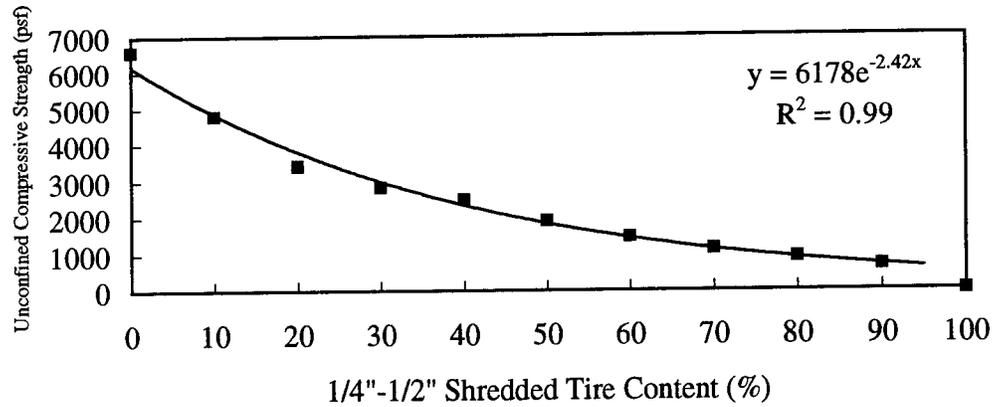


Figure 3.18 Unconfined compressive strength versus shredded tire content for clay-tire mixtures.

Table 3.9: F values for silt-tire mixtures containing different tire sizes, with different polynomial degrees and exponential function.

Silt-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2	Exponential
1/4"-1/2" Tire Chips	218.72	157.43	138.13
1/2"-1" Tire Chips	263.19	129.63	132.58
1"-1.5" Tire Chips	127.95	48.08	95.69

Table 3.10: F values for clay-tire mixtures containing different tire sizes, with different polynomial degrees and exponential function.

Clay-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2	Exponential
1/4"-1/2" Tire Chips	61.12	159.69	1543.7
1/2"-1" Tire Chips	51.5	122.76	1153.9
1"-1.5" Tire Chips	41.51	80.48	158.24

cohesive and lumpy than the silt soil and the failure planes along the contactive surface of soil and tire chips in caly-tire mixtures are easier development than in the silt-tire mixtures. Figures 3.17 and 3.18 show that mixtures containing bigger tire chips have higher rates of decrease of compressive strength than mixtures containing smaller tire chips for both silt-tire and clay-tire mixtures.

3.3.4 Consolidation Characteristics

The compression index is a measure of the compressibility of soil-tire mixtures. The compression index (C_c) was determined for both silt and clay, and for silt-tire and clay-tire mixtures containing 10% to 30% shredded tire by weight. The results of individual tests are shown in Appendix E. The plots of compression index value versus shredded tire content, and the corresponding regression lines, for silt-tire mixtures are presented in Figure 3.19 and for clay-tire mixtures in Figure 3.20. The F values for silt-tire mixtures with polynomial degrees of 1 and 2 are listed in Table 3.11 and for clay-tire mixtures in Table 3.12. For both soils and all three tire sizes, the F value is the highest when the polynomial degree is 1. Therefore, a linear equation was used to fit the compression index to shredded tire content.

The plots show that the compression index values increase with increase of shredded tire content as expected. Comparing both types of soil-tire mixtures, containing the same size of shredded tire material, shows that the rates of increase of compression index are similar for all three tire chip sizes. Comparison of silt-tire mixtures with clay-tire mixtures shows that the rate of increase of compression index is less for the silt-tire mixtures than

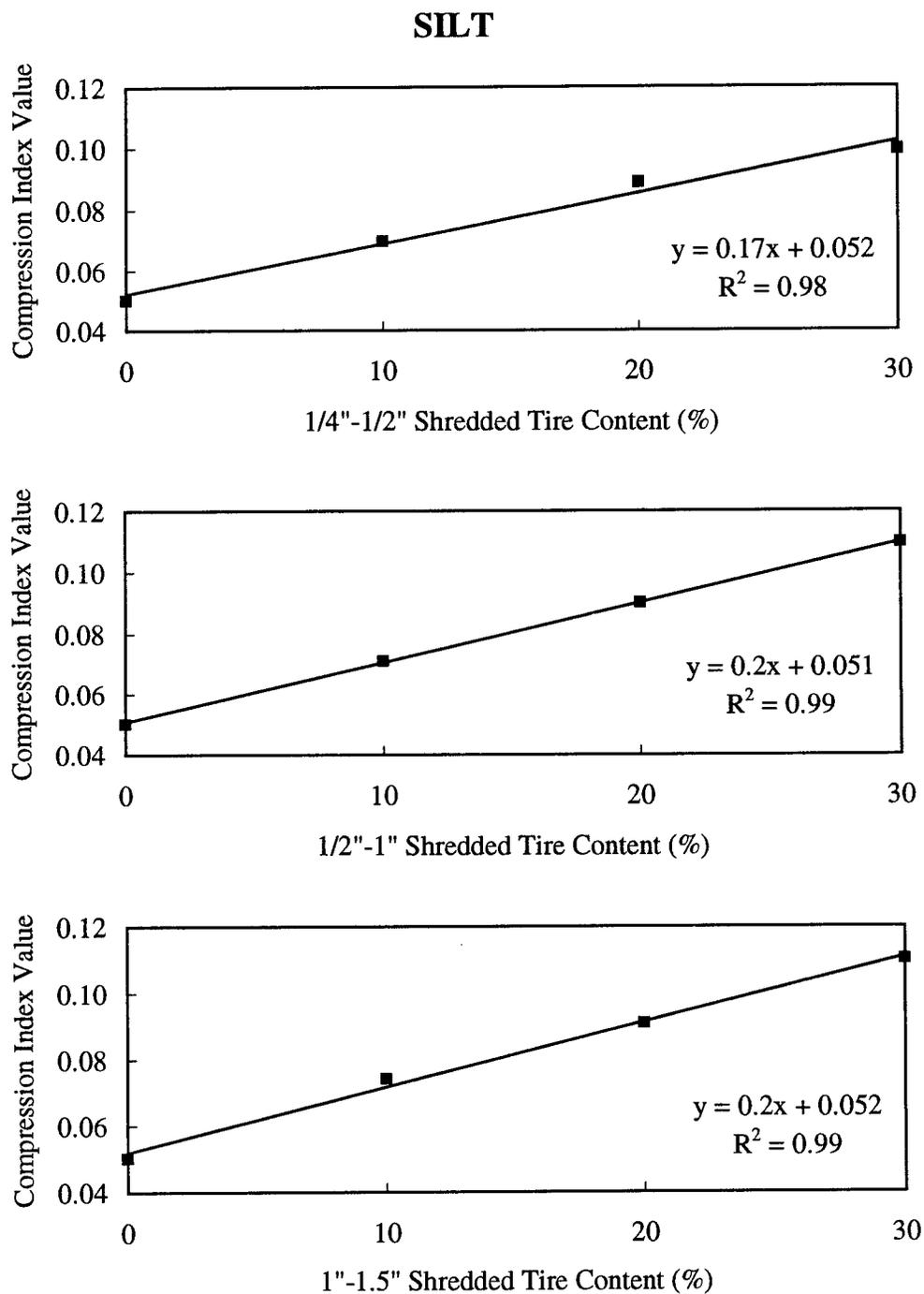


Figure 3.19 Compression index value versus shredded tire content for silt-tire mixtures.

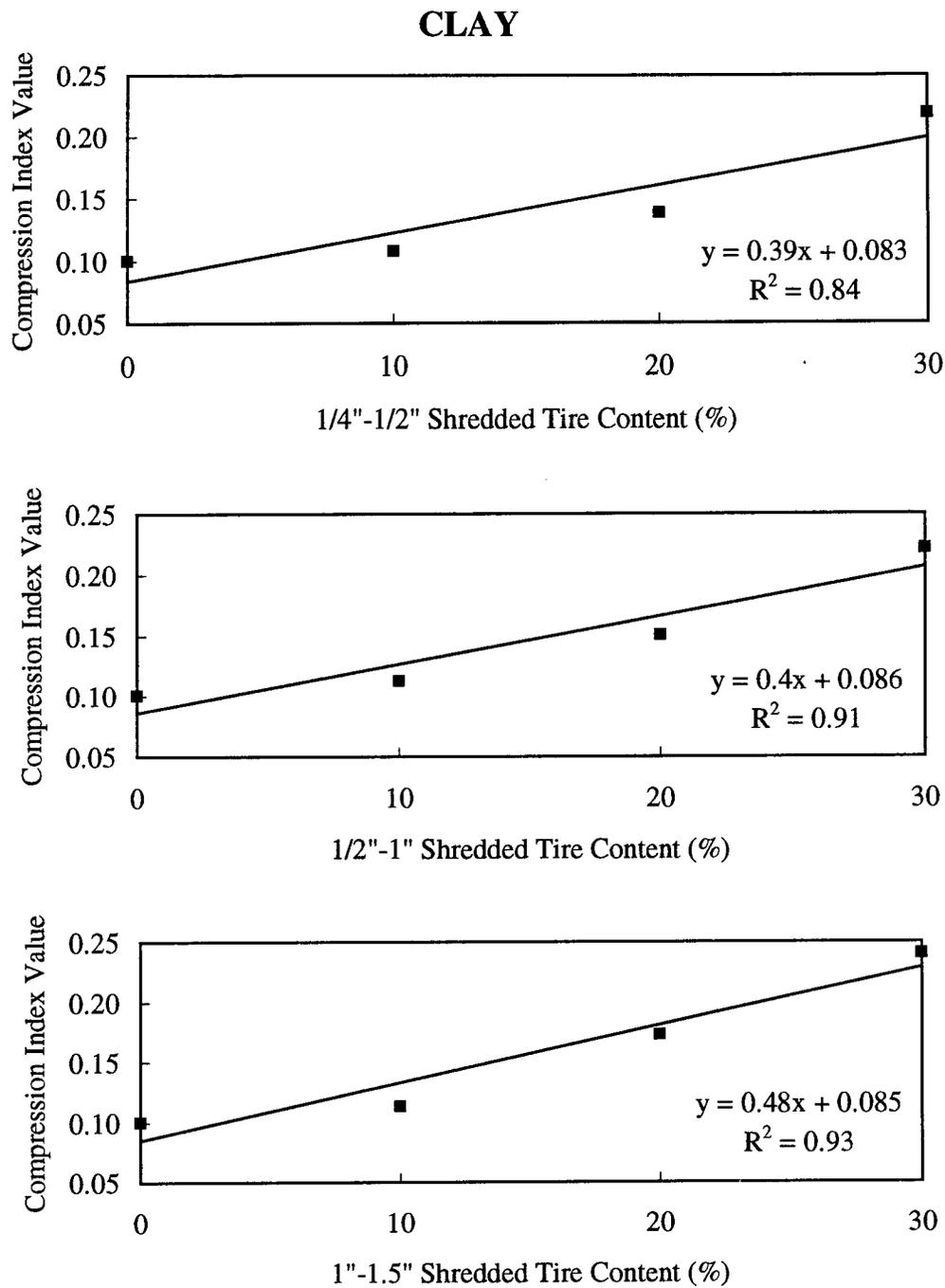


Figure 3.20 Compression index value versus shredded tire content for clay-tire mixtures.

Table 3.11: F values for silt-tire mixtures containing different tire chip sizes, with different polynomial degrees.

Silt-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2
1/4"-1/2" Tire Chips	112.7	10.81
1/2"-1" Tire Chips	328.6	19.1
1"-1.5" Tire Chips	89.63	28.58

Table 3.12: F values for clay-tire mixtures containing different tire chip sizes, with different polynomial degrees.

Clay-Tire Mixtures	Polynomial Degree = 1	Polynomial Degree = 2
1/4"-1/2" Tire Chips	181.8	65.43
1/2"-1" Tire Chips	622.6	54.76
1"-1.5" Tire Chips	228.5	54.71

the clay-tire mixtures. This indicates that for a given amount and size of shredded tire material, the clay-tire mixtures will be more compressible than the silt-tire mixtures.

3.4 Degradation Analysis

Rubber tires are designed to withstand the rigors of the environment so that they will last long on vehicles. Antioxidants and antiozonants, such as para-phenylene diamines, are added during the tire manufacturing process to attenuate deterioration (Morton, 1977). Therefore, it is not surprising that discarded tires persist for long periods. It has been estimated that whole tires take at least 100 years to decompose fully (Cadle and Williams, 1980). The shredded tire material, however, may degrade at a much faster rate than the whole tires.

The results of degradation test are shown in Table 3.13. Degradation is defined here as the ratio of the difference in the original and residual weights to the original weight, expressed as a percentage. For pure tire, 5.4% of tire by weight passed through the 1/4" (7 mm) sieve in the 1/4"-1/2" (7 mm-13 mm) size range, 3.3% of tire by weight passed through the 1/2" (13 mm) sieve in the 1/2"-1" (13 mm-25 mm) size range, and 2.3% of tire by weight passed through the 1" (25 mm) sieve in the 1"-1 1/2" (25 mm-38 mm) size range after 18 months of exposure to climate changes. This indicates that the amount of degradation increases with decreasing size of tire chips. These results are not unexpected as smaller tire chips have more surface area exposed to weathering agents.

For the soil-tire mixtures, 11.2% of tire by weight passed through the 1/4" (7 mm) sieve in the mixture of 70% silt and 30% 1/4"-1/2" (7 mm-13 mm) size tire material,

Table 3.13. Results of degradation test.

Contents	Original Weight (g)	Residual Weight (g)	Duration (%)
Pure Tire (1/4"-1/2")	44697	42281	5.41
Pure Tire (1/2"-1")	47382	45830	3.28
Pure Tire (1"-1.5")	43242	42232	2.34
70% Silt, 30% Tire (1/4"-1/2")	19898	17674	11.17
70% Clay, 30% Tire (1/4"-1/2")	15980	14228	10.97
40% Clay, 60% Tire (1/4"-1/2")	37544	34171	8.98

11.0% of tire by weight passed through the 1/4" (7 mm) sieve in the mixture of 70% clay and 30% 1/4"-1/2" (7 mm-13 mm) size tire material, and 9.0% of tire by weight passed through the 1/4" (7 mm) sieve in the mixture of 40% clay and 60% 1/4"-1/2" (7 mm-13 mm) tire. For both soil-tire mixtures, the degradation is similar when the proportions of tire chips are the same. This indicates that the soil types do not affect the degradation rate of tire chips. For clay-tire mixtures, a comparison of the amount of degradation between groups containing 0%, 30%, and 60% proportions of shredded tire material shows that the higher the percentage of soil in the mixture, the higher the amount of degradation. Similarly, mixing shredded tire material with silt increases the rate of degradation in silt-tire mixtures. The higher rate of degradation of tire chips in soil-tire mixtures compared to tire alone could be due to attack of soil micro-organisms (Jones et al, 1972), or atmospheric oxidation (Cadle and Williams, 1980).

3.5 Summary of Results

The maximum dry density decreases linearly with an increase in shredded tire content for both soil types and all three sizes of tire chips used in this study. For silt-tire mixtures, the maximum dry density decreases from 107 pcf (1.70 Mg/m³) for pure silt to nearly 53 pcf (0.85 Mg/m³) at 90% shredded tire content for all three sizes of tire chips. For clay-tire mixtures, the maximum dry density decreases from 103 pcf (1.65 Mg/m³) for pure clay to nearly 55 pcf (0.88 Mg/m³) at 90% shredded tire content for all three sizes of tire chips. For both soil-tire mixtures, the maximum dry density values are reduced to 2/3 of the values for soils alone at approximately 50% tire content, indicating that a lightweight fill

material can be produced by mixing 50% soil with 50% shredded tire material by weight.

The optimum water content decreases only slightly from 15% for pure silt soil and 16% for pure clay soil to nearly 14% at 50% shredded tire content for both soil-tire mixtures beyond which it shows a rapid decrease from 14% to less than 8% at 90% tire content for both soil types and all three tire sizes used.

The permeability of soil-tire mixtures was found to increase by six orders of magnitude from 10^{-7} cm/sec at 10% shredded tire content to 10^{-2} cm/sec at 40% shredded tire content for both soil types and all three sizes of tire chips. Beyond 40% tire content, the permeability of the mixtures increases only slightly from 10^{-2} cm/sec to 10^{-1} cm/sec at 10% shredded tire content for both soil types and all three sizes of tire chips.

For silt-tire mixtures, the friction angle increases from 30° for pure silt soil to 36° at 30% shredded tire content for all three sizes of tire chips. For clay-tire mixtures, however, the friction angle increases from 35° for pure clay soil to 38° at 20% shredded tire content, and then decreases to 31° at 30% shredded tire content for all three sizes of tire chips. Therefore, if improvement of the friction angle is the main concern, the amount of shredded tire material should not exceed 20% in clay-tire mixtures.

The cohesion values of soil-tire mixtures decrease to half of the cohesion values for original soils [1656 psf (79 KN/m^2) for silt and 2635 psf (126 KN/m^2) for clay] at 30% shredded tire content of 1/4"-1/2" (7 mm-13 mm) size range. For soil-tire mixtures containing the other two sizes of tire chips, the cohesion increases to 2800 psf (134 KN/m^2) for silt-tire mixtures and 3000 psf (144 KN/m^2) for clay-tire mixtures at 10%

shredded tire content by weight, and then drops to 2400 psf (115 KN/m²) for silt-tire mixtures and 2700 psf (129 KN/m²) for clay-tire mixtures at 30% shredded tire content.

The unconfined compressive strength decreases with an increase of shredded tire content for both soil types and all three size ranges of shredded tire. For silt-tire mixtures, the unconfined compressive strength decreases from 4077 psf (195 KN/m²) for pure silt to zero around 50% shredded tire content for all three size ranges of tire chips. For clay-tire mixtures, the unconfined compressive strength drops from 6600 psf (316 KN/m²) for pure clay soil to zero around 80% shredded tire content for the two smaller size ranges (1/4"-1/2", 7 mm-13 mm and 1/2"-1", 13 mm-25 mm) of tire chips, and to 490 psf (24 KN/m²) at 50% shredded tire content for the 1"-1.5" (25 mm-38 mm) size of tire chips.

The compression index values for the two soil types (0.05 for silt soil and 0.10 for clay soil) are doubled at 30% shredded tire content for all three sizes of tire chips, implying that settlement will increase with increasing shredded tire content.

The degradation values of shredded tire material upon exposure to changing climatic conditions are 2.34%, 3.28%, and 5.41% for 1/4"-1/2" (7 mm-13 mm) size of tire chips, 1/2"-1" (13 mm-25 mm) size of tire chips, and 1"-1.5" (25 mm-38 mm) size of tire chips, respectively. The degradation of shredded tire material increases from 5.41% for pure tire chips to 10.97% for clay-tire mixtures containing 30% shredded tire content of 1/4"-1/2" (7 mm-13 mm) size range and 11.17% for silt-tire mixtures containing 30% shredded tire content of 1/4"-1/2" (7 mm-13 mm) size range. The degradation test revealed that the smaller tire chips and the higher soil proportions result in higher amount of tire

degradation.



CHAPTER 4

CONSTRUCTION AND PERFORMANCE OF THE SOIL-TIRE TEST EMBANKMENT

4.1 Introduction

In order to evaluate the field performance of tire-stabilized soils as a lightweight fill material, a test embankment was constructed on the campus of Kent State University, Kent, Ohio. In designing the test embankment, factors including soil types, tire chip sizes, and the ratio of soil to tire chips were considered. Since clays exhibit the worst properties in the field, especially when it is wet, the clay soil (CL) used in the laboratory study and the 1/2"-1" (13 mm-25 mm) size shredded tire material were ultimately chosen to build the test embankment. The mixture had a soil : tire ratio of 70% : 30% by weight. The engineering properties of the field mixture are presented in Table 4.1. A gravel soil, classified as a GP according to the USCS, was used as a filter material in embankment construction. The grain size distributions of the clay soil, the shredded tire material, and the gravel soil are shown in Figure 4.1.

It was important to prevent the surface water or ground water from the surrounding area flowing into the test embankment and the leachate from the embankment flowing into the surrounding area. To accomplish this, a synthetic liner was placed at the bottom of the embankment before the construction of the embankment. Four lysimeters, reaching depths

Table 4.1: Engineering properties of the clay-tire mixture used for embankment construction.

Physical Properties	70% Clay with 30% 1/2"-1" Size Shredded Tire Material
Optimum Water Content (%)	14.6
Maximum Dry Density (pcf)	84
Permeability (cm/sec)	8.83E-03
Friction Angle (°)	38
Cohesion (psf)	2606
Unconfined Compressive Strength (psf)	2630
Compression Index (Cc)	0.22

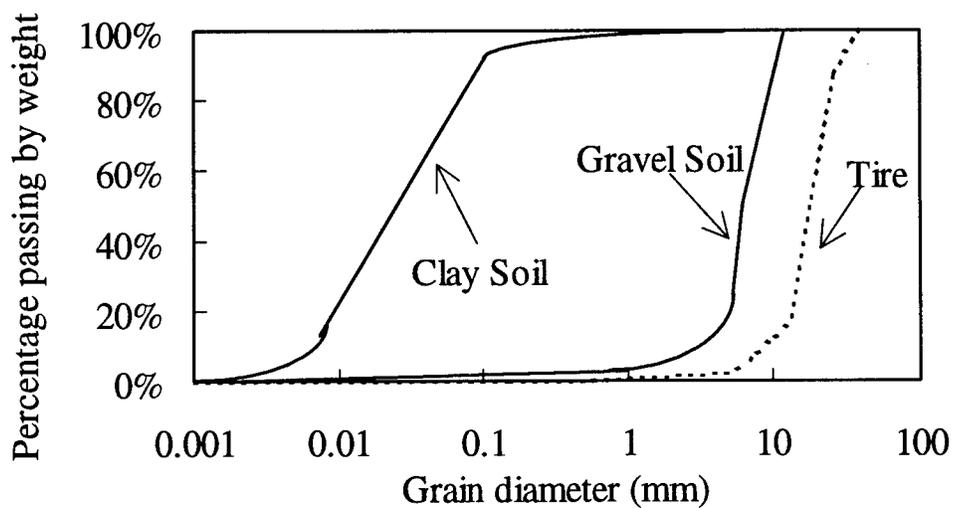


Figure 4.1: The grain size distribution of shredded tire, gravel, and foundation soil.

of 1, 2, 3, and 4 feet (0.3m, 0.6m, 0.9m, and 1.2m), respectively, from the embankment top, were installed along the center line of the embankment (Figure 4.2) and were used for periodic collection of the leachate generated in the field. Also, two perforated pipes were installed to collect leachate, one along the perimeter of the embankment bottom and the other at 2 feet (0.6 m) height from the embankment bottom, transversing the middle of the test embankment (Figure 4.2).

The following specifications and dimensions were used for embankment construction:

Density	> 95% of MDD.
Water Content	± 2% of OWC.
Lift Thickness	1 ft. (0.3m)
Length	50 ft. (15m)
Height	4.5 ft. (1.5m)
Crest Width	8 ft. (2.4m)
Bottom Width	22 ft. (6.6m)
Side Slopes	33.4° and 35.6°

4.2 Construction Process

After scraping off the surface grass, a smooth-wheel roller was used to level the ground and compact it slightly. A synthetic liner was then placed to separate the foundation soil from the embankment materials (Figure 4.3). An elevation survey was made of the foundation base and a reference point, some distance away from the base, was set for the observation of the crest settlement in the future. A drainage system was then

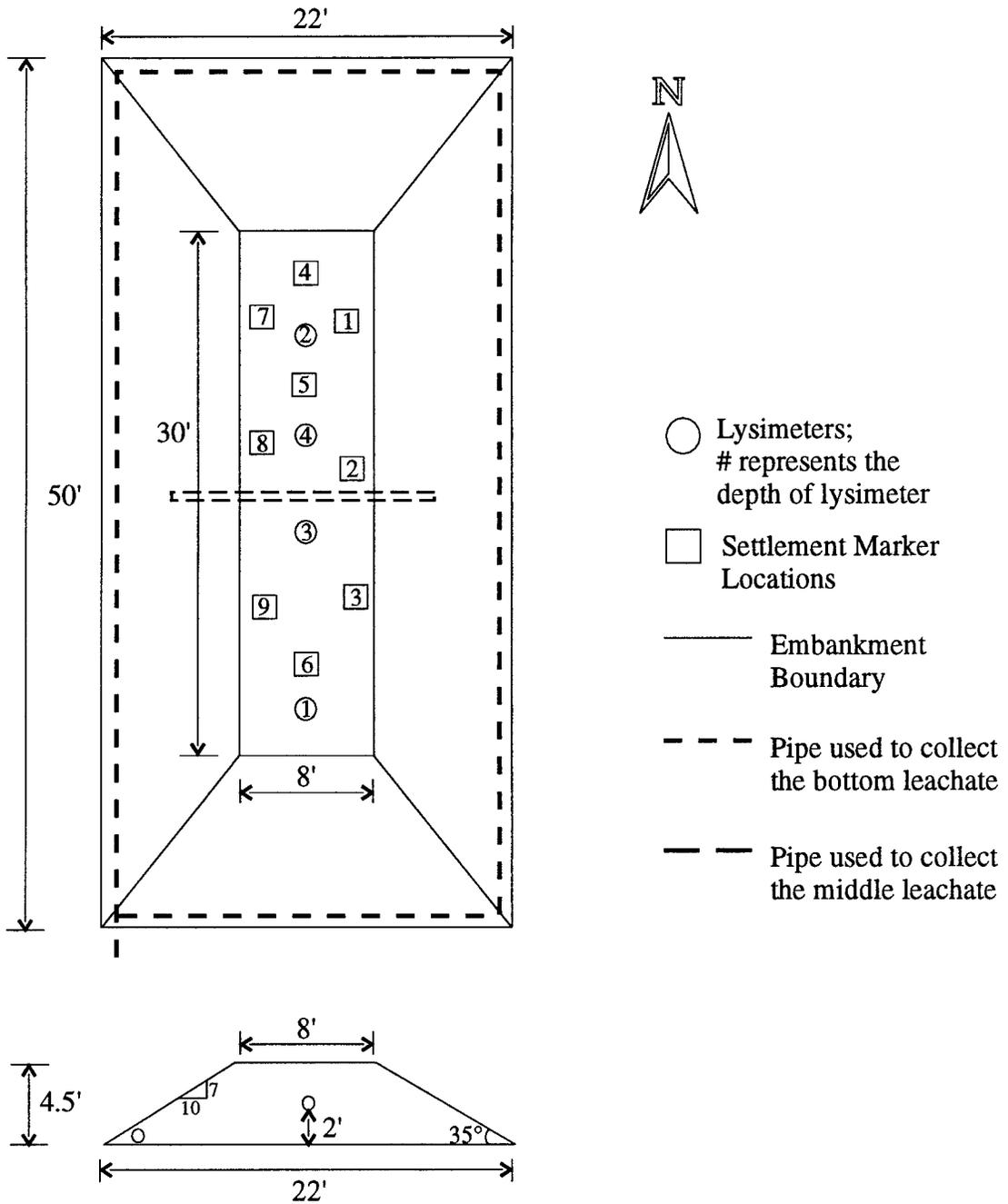


Figure 4.2: The plan view (top) and cross-section (bottom) of the test embankment.



Figure 4.3: An overview of the synthetic liner that was used to separate the foundation soil from the embankment materials.

installed. Perforated pipes, with 0.2-inch (4.75 mm) size holes, were placed on the synthetic liner, along the perimeter of the embankment, and then covered by the gravel soil (Figure 4.4) to prevent piping of the clay soil into the holes. After the drainage system was covered by the gravel soil, the test embankment was constructed in five lifts with each lift being approximately 1-foot (0.3 m) thick. During the construction of each lift, the clay soil was spread first on the bottom and shredded tire material was spread on top of clay soil by a bulldozer. A rototiller, attached to a tractor, was then used to mix the soil and shredded tire material (Figure 4.5). After mixing the soil and shredded tire material, a smooth-wheel roller was used to compact the first two lifts and a sheepsfoot roller was used to compact the remaining three lifts. Measurements of lift thickness were made after compaction of each lift. A second drainage system was installed in the middle of embankment after finishing the third lift. A 1-foot (0.3 m) deep trench, perpendicular to embankment axis, near the middle portion, was dug using a power shovel. A 6-inch (15 cm) diameter perforated pipe was put in the trench and covered by gravel (Figure 4.6). The pipe and gravel were the same type as those used for the bottom drainage system.

Observations during the construction process indicated that a rototiller, attached to a tractor, can mix the tire chips with the soil quite well but the size of the tractor affects the depth of the mixing. The smooth-wheel roller can compact the soil-tire mixture adequately but it does not offer any mixing effect. The sheepsfoot roller can mix the soil and tire chips as well as compact the soil-tire mixture. It begins compacting the soil-tire mixture below the bottom of the foot and works its way up the lift as the number of passes increases. The sheepsfoot roller turns up soil and tire chips and compacts them by its own weight.



Figure 4.4: Covering of the perforated pipes by gravel soil to prevent piping of the clay soil into the holes.



Figure 4.5: Rototiller, attached to a tractor, that was used to mix the soil and shredded tire material.



Figure 4.6: The second drainage system near the middle portion of the embankment consisting of a perforated pipe placed in a trench perpendicular to the embankment axis and covered with gravel filter.

Eventually, the lift can be mixed and compacted well.

4.3 Instrumentation

An instrumentation system was designed to evaluate the performance of the test embankment. The compressibility of the test embankment was monitored by regularly performed surveys of surface markers located on the top of the test embankment. The surface markers were placed at nine locations, with three of them in one line, as shown in Figure 4.2. From north to south, the locations of surface marker were labeled as S1, S2, and S3, respectively, on the east side of the embankment, as S4, S5, and S6 in the middle portion, and as S7, S8, and S9 on the west side. Each surface marker consisted of an 18-foot x 18-foot (46 cm x 46 cm) square, 0.25-inch (0.64 cm) thick, plastic plate with a 38-inch (97 cm) high rod installed perpendicular to the base near its center. A Wild T-2 theodolite was used to measure the elevation of the surface marker at each location from the base of the embankment. The elevation of the top of the embankment at each location was obtained by subtracting the length of rod and the thickness of plastic plate from the elevation of the surface marker.

Four lysimeters reaching depths of 1, 2, 3, and 4 feet (0.3m, 0.6m, 0.9m, and 1.2m), respectively, from the embankment top were installed for collection of leachate (Figure 4.2). The lysimeters consisted of 2-inch (5 cm) diameter PVC pipes wrapped in the filter fabric material. The screen of the pipe was surrounded by pure quartz sand to let the leachate flow into the pipes. A montmorillonite plug was put above the sand to prevent other influxion and to make sure the leachate was collected from the specific depth. The

schematics of lysimeter cross sections are shown in Figure 4.7 whereas Figure 4.8 presents an overview of the test embankment and lysimeter locations.

4.4 Performance

Observations were made of the stability of the side slopes, settlement of the crest, development of tension cracks, and of any other signs of embankment deterioration. Surveys including measurement of the elevation of the surface markers and the slope angles of the embankment were conducted periodically. The elevation data of the markers revealed the amount of settlement of the embankment crest. The slope angles of the embankment versus time measurements were used to study any creep effects. The results of these surveys permitted a quantitative evaluation of the performance of the embankment.

The survey date and the settlement data collected from the nine surface markers are shown in Appendix F. The plots in Figure 4.9 represent the crest height, as measured from the reference point, on both sides of the embankment (Line S1-S3 and Line S7-S9) as well as the crest height near the middle of the embankment (line S4-S6). Measurements indicate that settlement occurred rapidly during the first 120 days (4 months) after construction. In the first four months, the settlement was 4 inches (10 cm) at S1, 5 inches (13 cm) at S2, and 8 inches (20 cm) at S3 on the eastern side, 2 inches (5 cm) at S4, 3 inches (8 cm) at S5, and 5 inches (13 cm) at S6 in the middle, and 3 inches (8 cm) at S7, 4 inches (10 cm) at S8, and 6 inches (12 cm) at S9 on the western side. After 120 days from construction, very little additional settlement occurred and its rate slowed down

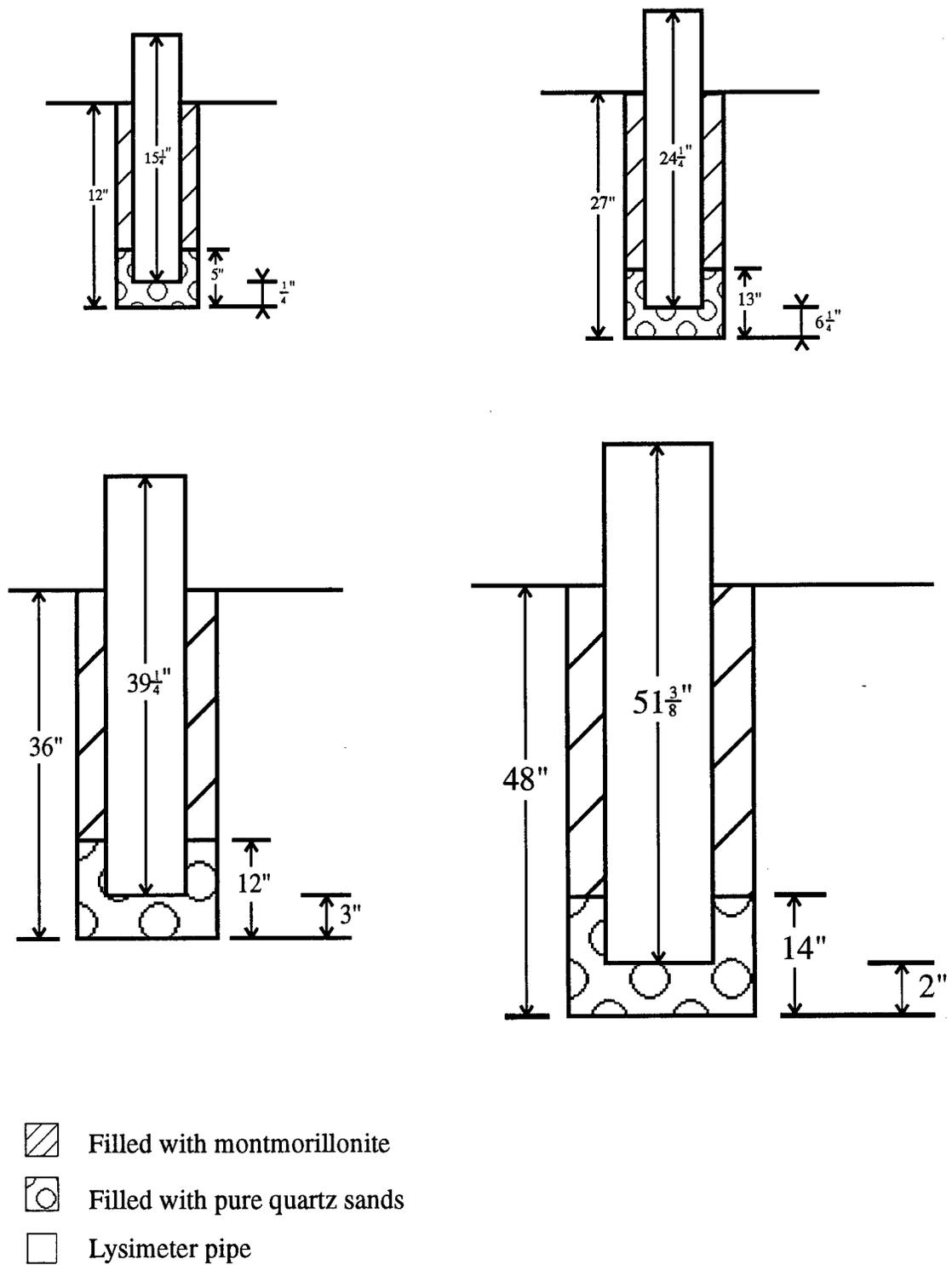


Figure 4.7 Schematic cross sections of the four lysimeters.



Figure 4.8: Overview of the test embankment; four white pipes on the top of the embankment indicate the positions of the lysimeters.

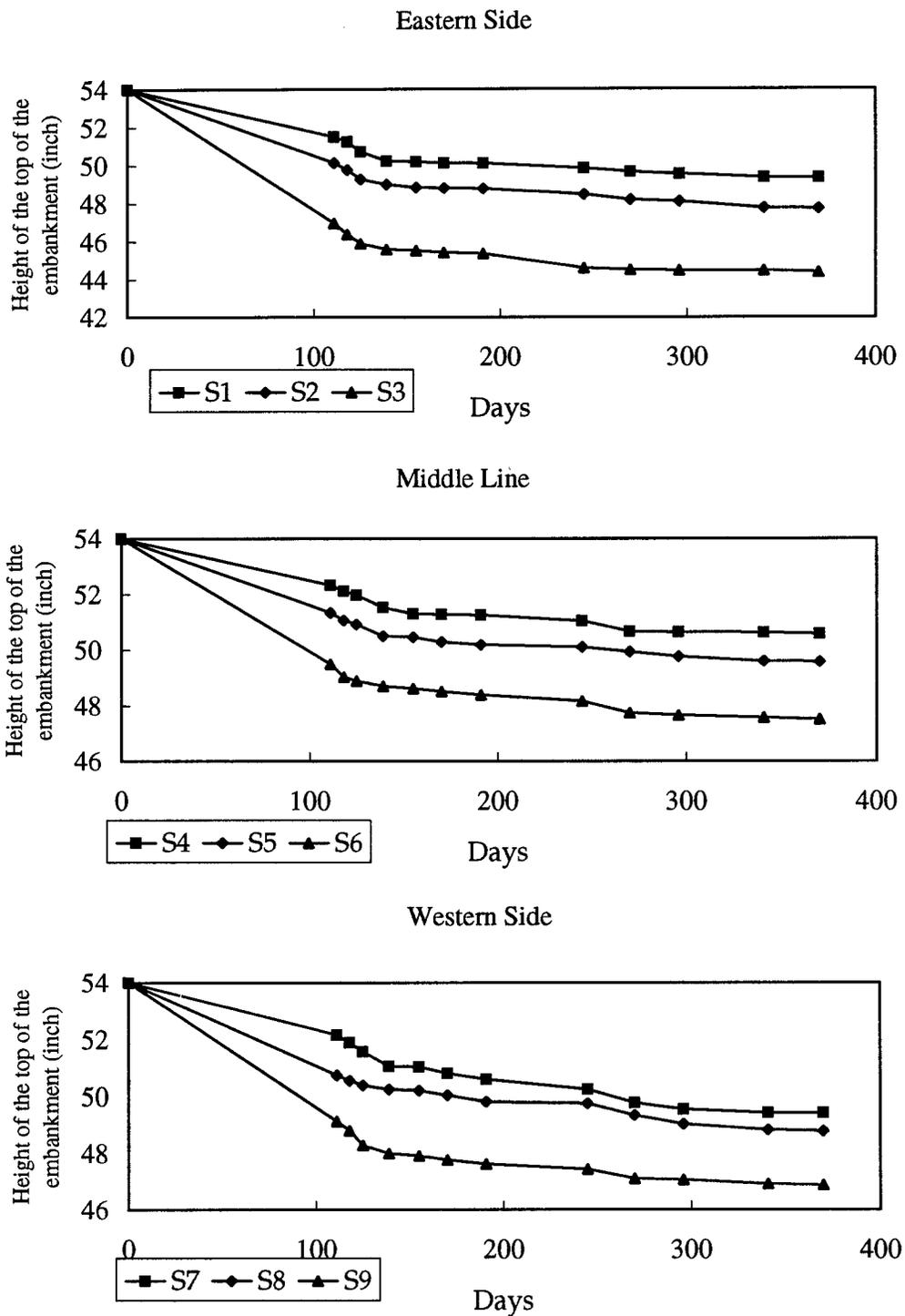


Figure 4.9 Settlement of embankment crest vs. Days after construction.

considerably. Comparing the amount of settlement in the middle with that on both sides, it is apparent that the settlement in the middle (S4, S5, and S6) is less than that on the two sides (S1, S2, S3, S7, S8, and S9). Also, the settlement is the least at the northern end (S1, S4, and S7) and it is the most at the southern end (S3, S6, and S9) for the three different lines of settlement markers. Comparing the eastern and western sides of the top of the embankment, the settlement is similar at the northern end of the embankment (S1, S4, and S7) but the settlement on the eastern side (S3) is more than that on the western side (S9) at the southern end of the embankment.

An explanation of the settlement behavior of the embankment top is as follows. During the construction of the embankment, the tractor carrying the rototiller went forward from southern end to northern end on the western side of the embankment. After reaching the northern end, the tractor U-turned and went back to the southern end moving along the eastern side of the embankment. After the tractor reached the southern end, it left the embankment to start a new pass. As the size of the rototiller was more than half the width of the embankment, the middle of the embankment was compacted more than the sides due to overlap. The better compaction in the middle of the embankment, therefore, resulted in the lower amount of settlement in the middle strip. Similarly, the more compactive effort on the northern end, due to U-turns, than on the southern end of the embankment is responsible for less settlement on the northern side of the embankment under the situation of equal thickness of the embankment everywhere.

The survey date and the data gathered from observations of slope angle for both sides of the test embankment are shown in Appendix G. The relationship between slope angles

and days after construction are shown in Figure 4.10. Because of the irregular nature of the slope surface, due to the presence of tire chips, the slope angles are considered as the same if the difference of slope angles is less than five degrees. Therefore, the plots in Figure 4.10 reveal that the slope angles did not change with time on either side of the embankment, suggesting that no apparent creep has occurred since the construction of the embankment.

4.5 Slope Stability Analysis

The software program STABL4M, developed at Purdue University, was adopted to evaluate the stability of embankment slopes of varying heights and angles. In the STABL4M, the input parameters including engineering properties of construction material, heights and angles of the embankment slopes, and saturation conditions were used to calculate the factor of safety for each potential failure plane. The lowest value in the computational results was chosen to represent the factor of safety of the specific slope height and slope angle. A multivariable regression was adopted to generate a formula showing the relationship between slope height, slope angle, and the factor of safety for given engineering properties of the material and the saturation conditions.

The engineering properties of construction materials, used in stability analysis, are given in Table 4.1. Since I do not expect the soil-tire mixtures to be used for slopes higher than 100 feet (30.5 meter), in this research the slope height was chosen to range from 0 to 100 feet (0 to 30.5 meter). The range of slope angle used was from 0 to 60 degrees because embankments rarely have slope angles exceeding 60 degrees. Two drainage

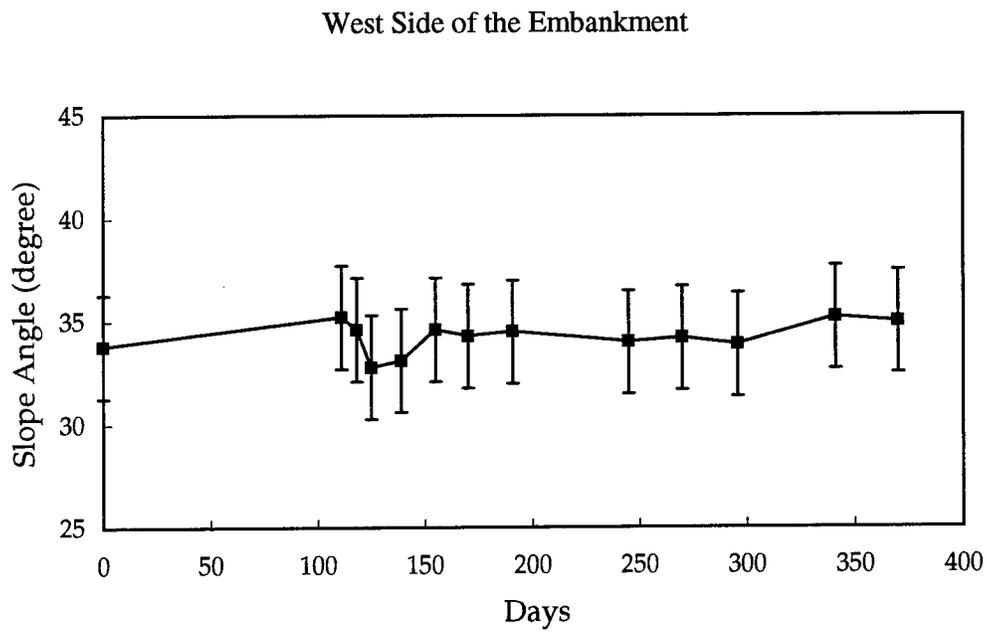
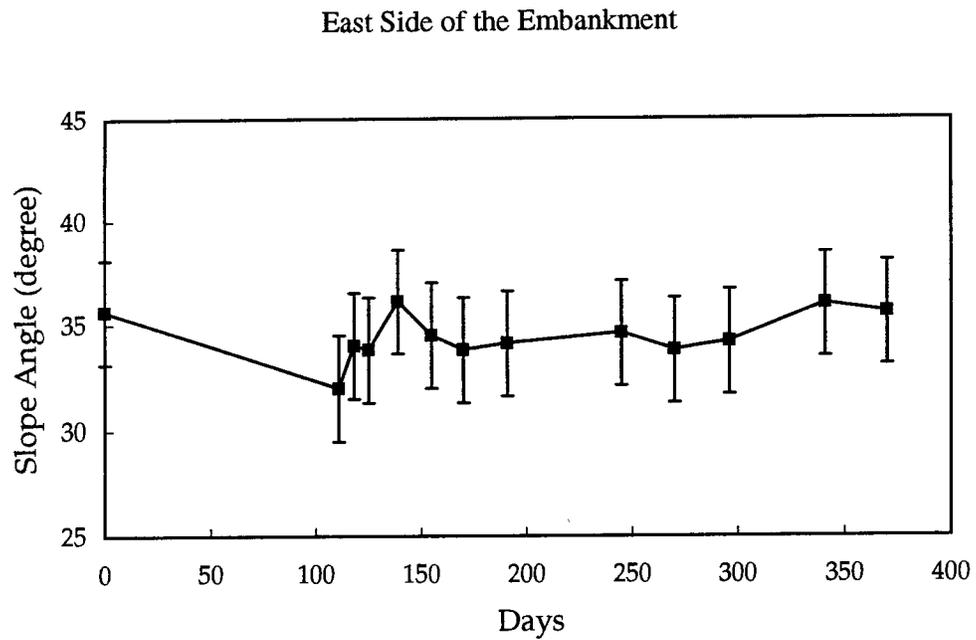


Figure 4.10: Slope angles of both sides of the embankment vs. time in days. The vertical bar through each data point represents error range of 2.5 degrees.

conditions were considered for the stability analysis: dry condition and full saturation condition. For a dry situation with no pore pressure development, the formula is as follows:

$$FS = 3.94 - 0.02h - 0.02\theta + 22.03/\theta \quad (4.1)$$

where FS is factor of safety, h is slope height (feet), and θ is slope angle (degrees). For a full saturation conditions, the formula is as follows:

$$FS = -1.02 - 0.01h + 0.07\theta + 44.91/\theta \quad (4.2)$$

The relationships between slope height, slope angle, and factor of safety are shown in Figure 4.11 for the two drainage conditions. The plots in Figure 4.11 show that an increase in either the slope height or the slope angle can result in a lower factor of safety. For a given slope height and slope angle, the factor of safety is lower under saturated conditions than under dry conditions. For a given factor of safety under the dry conditions, the allowable maximum height of slope decreases dramatically with increasing slope angle when the angle is less than 40 degrees, but the decrease is much more gradual when the slope angle is higher than 40 degrees. For a given factor of safety under the saturation conditions, the acceptable maximum height decreases dramatically with increasing slope angle when the slope angle is less than 30 degrees, but it does not change much with increase of slope angle when the slope angle is higher than 30 degrees for a given factor of safety value.

The height of the test embankment for this research is 4.5 feet (1.4 m) and the slope angle is 35°. The factor of safety for the test embankment is 4.1 under dry conditions, and

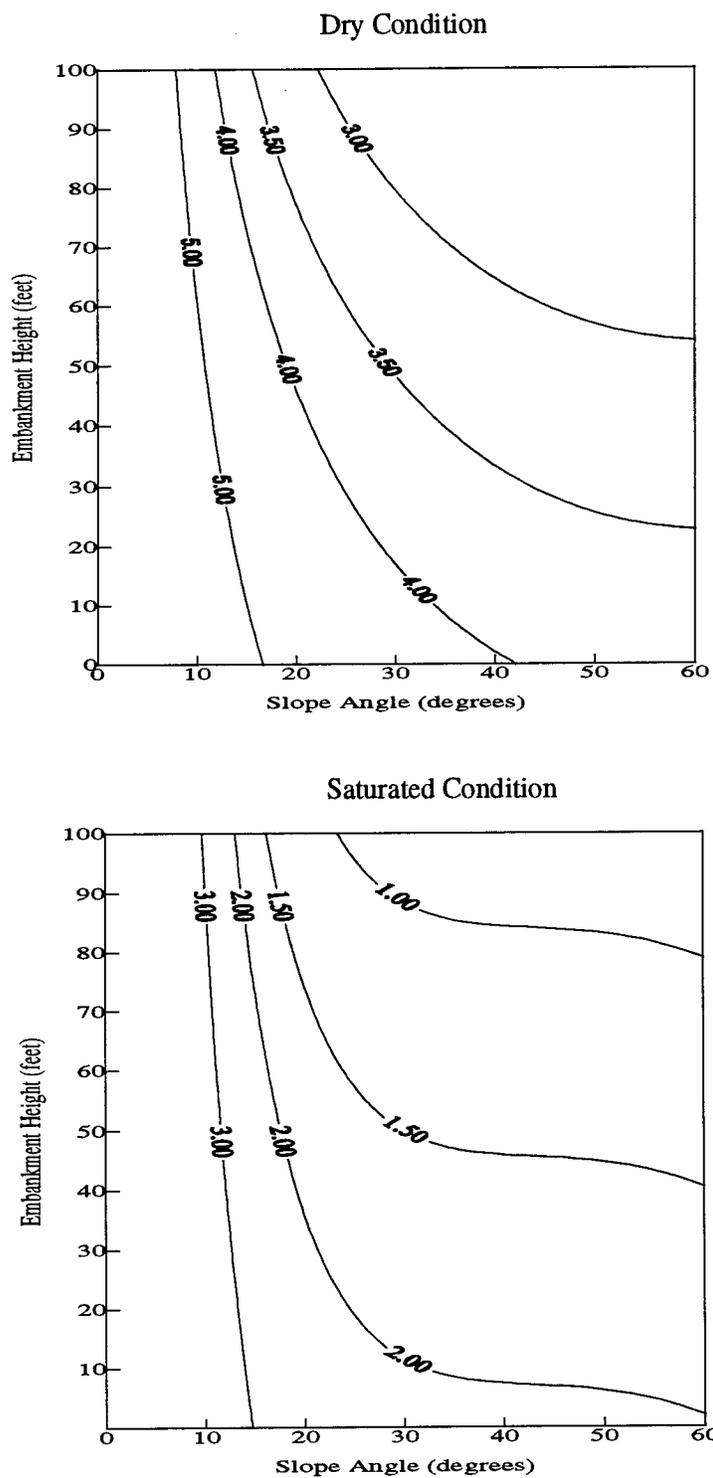


Figure 4.11: Relationships between slope height, slope angle, and factor of safety. The numbers on the curves represent F.S. values.

2.1 under saturated conditions, based on the equations 4.1 and 4.2, respectively. Thus, slope instability is not a matter of concern for the test embankment used in this study, even under the worst possible situation.

Since the soil-tire mixtures, containing 70% clay and 30% shredded tire of 1/2"-1" (13 mm-25 mm) size range, have high permeability values, saturated conditions are not likely to prevail in general. However, under some conditions, such as continual heavy rainfall or failure of drainage system, the full saturation conditions could develop.

4.6 Summary of Results

The test embankment data show that it is possible to use soil-tire mixtures for building embankments. The rototiller appears to be the most appropriate means of mixing soil and tire chips. Also, the sheepsfoot roller is quite suitable for mixing and compacting soil-tire mixtures adequately. Results of the settlement survey show that most of the crest settlement occurred in the first four months after which the rate of settlement slowed down significantly. The settlement was 4 inches (10 cm) at S1, 5 inches (13 cm) at S2, and 8 inches (20 cm) at S3 on the eastern side, 2 inches (5 cm) at S4, 3 inches (8 cm) at S5, and 5 inches (13 cm) at S6 in the middle, and 3 inches (8 cm) at S7, 4 inches (10 cm) at S8, and 6 inches (12 cm) at S9 on the western side of the embankment during the first four months. The slope angles of both sides of the test embankment were found to be almost constant with time.

Two equations were derived for quick evaluation of the factor of safety values for embankments of different heights and slope angles and for the specific engineering

properties of soil-tire mixtures shown in Table 4.1. Based on these equations, the test embankment has a factor of safety of 4.1 under dry conditions and of 2.1 under saturated conditions.

CHAPTER 5
CHEMICAL CHARACTERIZATION OF SHREDDED SCRAP TIRE AND
SOIL-TIRE MIXTURES

5.1 Introduction

If shredded scrap tires are to be used in soil stabilization, the potential environmental impacts of such a usage have to be evaluated. A major concern about the use of shredded scrap tire is the potential for toxic substances to leach from the material upon interaction with water, thus posing a threat to surface and ground water resources. In order to address these concerns, the loss on ignition and bulk composition were investigated. In addition, the leachate from soil-tire mixtures was analyzed for trace element chemistry. The results were compared with those of similar studies by other researchers (Grefe, 1989; MPCA, 1990; RMA, 1990; Edil and Bosscher, 1992; Bosscher et al., 1993; Black and Shakoor, 1994; Humphrey et al., 1997).

5.2 Background Information

Tires are a heterogeneous mixture of vulcanized or cross-linked polymers, carbon black, dispersing oil, synthetic fibers, pigments, processing chemicals, and steel or fiberglass. Various parts of the tire construction require specific rubber properties. These different requirements call for different compounds having a range of polymer systems and chemical elements (Hemphill, 1990). The chemical composition of tires, as expressed

by production or element analysis, can be quite variable and difficult to specify. Several studies have been done to determine the chemical components of different kinds of shredded tire (Crane, et al., 1978; Ahmed, 1992; Holland et al., 1993). An approximate chemical analysis, by Crane et al. (1978), of scrap tire material indicates the presence of the following contents: carbon (83%), hydrogen (7.1%), oxygen (2.5%), sulfur (1.2%), and nitrogen (0.3%). The remaining material (5.9%) is nonvolatile ash. Ahmed (1992) found the major components of scrap tire to include synthetic or natural rubber (50%), carbon black (27.5%), and oil (17.5%). The range of rubber hydrocarbon was from 41.5% to 54.9%, carbon black from 30% to 36.9%, acetone extraction from 10% to 19.1%, and ash from 3.7% to 6.6% in the study by Holland et al. (1993).

5.3 Chemical Analyses

In order to test the chemical characteristics of shredded scrap tires, the following analyses were performed: loss on ignition, bulk analysis, and leachate analysis. For the loss on ignition and bulk analysis, three different tire sizes (1/4"-1/2" or 7 mm-13 mm, 1/2"-1" or 13 mm-25 mm, and 1"-1.5" or 25 mm-38 mm) were used. The steel and nylon chords had already been removed from the smaller size range (1/4"-1/2" or 7 mm-13 mm) of shredded tire material by the supplier, resulting in steel-free tire shreds. However, the steel and nylon chords in the other two sizes (1/2"-1" or 13 mm-25 mm and 1"-1.5" or 25 mm-38 mm) had not been removed completely. The steel and nylon chords in those tire sizes were treated as a part of the tire when analyzed for chemical composition. For the leachate analysis, two different sources of leachate were used: one was prepared following the EPA

toxicity test procedure (EPA, 1990) in the laboratory, and the other was collected from the soil-tire mixtures exposed to natural conditions in the field.

5.3.1 Loss on Ignition

The LOI values of twenty samples for each tire size range are shown in Appendix H. Summary results of the LOI tests are shown in Table 5.1. The value of mean is the average of twenty samples and the value of standard deviation represents the variability of twenty samples for each size range of tire chips. The LOI values range from 65.83% to 75.47% with a mean of 70.03% for 1/4"-1/2" (7 mm-13 mm) size tire chips, from 63.49% to 87.18% with a mean of 71.74% for 1/2"-1" (13 mm-25 mm) size tire chips, and from 57.68% to 83.75% with a mean of 70.86% for 1"-1.5" (25 mm-38 mm) size tire chips. To assess the effect of tire chip sizes on the mean LOI values, the t-test was applied. The testing hypothesis and significance level for comparison of LOI and tire chip size range, the p-value, and the decisions for distinguishing between any two tire chip sizes are presented in Table 5.2. The results show that there is no significant difference in LOI values between tire chip sizes and whether or not steel and nylon chords exist.

5.3.2 Bulk Analysis

The detection limits, precision, and concentrations of each element in different size ranges of tire chips used for bulk chemical analysis are shown in Appendix I. As the concentration of each element, a sample was measured three times and the average was taken for further usage. The summary results of bulk chemical analysis for the three size ranges of shredded tire material are presented in Table 5.3. The value of mean is the

Table 5.1: Results of loss on ignition (LOI) test.

LOI (%)	Tire Size		
	1/4"-1/2"	1/2"-1"	1"-1.5"
n	20	20	20
High	75.47	87.18	83.75
Low	65.83	63.49	57.68
Average	70.03	71.74	70.86
Std. Dev.	2.59	4.89	7.54

Table 5.2: Results of t-test performed to assess the effect of tire size on LOI value.

Test Hypotheses: $H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$ Critical Value: $\alpha = 0.05$		
Parameter	Test Statistic: p-Value	Decision
LOI Test	0.64 ($\mu_A; \mu_B$) 0.82 ($\mu_A; \mu_C$) 0.81 ($\mu_B; \mu_C$)	$\mu_A = \mu_B = \mu_C$

A represents 1/2"-1/4"; B represents 1/2"-1"; C represents 1"-1.5"

Table 5.3: Results of normalized bulk chemical analyses.

Ion Concentration (mg ion/kg shredded tire material)	Shredded Tire Size Range					
	1/4"-1/2"		1/2"-1"		1"-1.5"	
	mean	Std.*	mean	Std.*	mean	Std.*
Al	0.99	0.55	1.01	0.33	1.15	0.39
Ba	3.19	0.89	3.06	1.78	3.20	1.85
Ca	1.82	0.48	1.97	0.89	1.58	0.45
Cd	0.02	0.01	0.02	0.01	0.03	0.02
Co	0.91	0.77	0.95	0.84	1.05	0.64
Cr	0.21	0.11	0.25	0.14	0.29	0.18
Cu	0.03	0.01	0.04	0.01	0.04	0.01
Fe	405	140	707	289	732	368
Mn	1.65	0.64	3.04	1.49	3.05	1.37
Pb	0.34	0.22	0.70	0.12	0.72	0.15
Zn	2030	671	3270	963	3250	885

* Std. = Standard deviation about the mean for analyzed samples; twenty samples analyzed in each tire size range and each sample was analyzed three times.

average of twenty samples and the value of standard deviation is the spread state of these twenty samples. The measured concentrations in solution were normalized by the following conversions:

$$\text{concentration (mg/l)} \times 0.1 \text{ l solvent} + \text{dissolved solid (g)} = \text{concentration (mg ion/kg shredded tire material)}$$

The bulk chemistry gives some indication of the amount of metallic constituents which could leach out under a "worst situation", that is if the shredded tires were to degrade completely and all inorganic components were to be released. Table 5.3 shows that the concentrations of iron and zinc are high for all three tire sizes while others are low.

In order to evaluate the effect of shredded tire sizes on concentrations of various elements, the t-test was performed. The testing hypothesis, significance level, p-values, and decisions for distinguishing between any two tire sizes for different elements are presented in Table 5.4. In Table 5.4, the subscripts, A, B, and C, designate the three size ranges of shredded tire material. For the smallest size range (1/4"-1/2" or 7 mm-13 mm) of shredded tire material, the concentrations of iron, manganese, lead, and zinc are lower than for the two bigger size ranges (1/2"-1" or 13 mm-25 mm and 1"-1.5" or 25 mm-38 mm) of shredded tire material since the steel and nylon chords were left in the two bigger size ranges. For the two bigger size ranges of shredded tire, the concentrations of these elements are not significantly different. The test results also show that there is no significant difference between concentrations of other elements. Kovac (1978) indicated that the proportion of trace elements in the steel used for the manufacturing of tire chords was as follows: zinc (1%), magnesium (0.5%), silicon (0.3%), lead (< 0.03%), sulfur (<

Table 5.4: Results of t-test to assess the effect of tire size on bulk chemistry.

Test Hypotheses: $H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$ Critical Value: $\alpha = 0.005$		
Elements	Test Statistic: p-Value	Decision
Al	0.87 ($\mu_A:\mu_B$); 0.30 ($\mu_A:\mu_C$); 0.28 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Ba	0.76 ($\mu_A:\mu_B$); 0.99 ($\mu_A:\mu_C$); 0.83 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Ca	0.53 ($\mu_A:\mu_B$); 0.11 ($\mu_A:\mu_C$); 0.12 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cd	0.44 ($\mu_A:\mu_B$); 0.005 ($\mu_A:\mu_C$); 0.10 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Co	0.83 ($\mu_A:\mu_B$); 0.48 ($\mu_A:\mu_C$); 0.68 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cr	0.26 ($\mu_A:\mu_B$); 0.13 ($\mu_A:\mu_C$); 0.48 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cu	0.10 ($\mu_A:\mu_B$); 0.006 ($\mu_A:\mu_C$); 0.06 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Fe	0.0004 ($\mu_A:\mu_B$); 0.003 ($\mu_A:\mu_C$); 0.85 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Mn	0.002 ($\mu_A:\mu_B$); 0.004 ($\mu_A:\mu_C$); 0.99 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Pb	0 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0.08 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Zn	0.0002 ($\mu_A:\mu_B$); 0.0001 ($\mu_A:\mu_C$); 0.94 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$

A represents 1/2"-1/4"; B represents 1/2"-1"; C represents 1"-1.5"

0.05%) and phosphorus (< 0.03%). Therefore, the higher concentration of iron, lead, zinc, and manganese found in this study (Table 5.3) were expected in both bigger size ranges of tire chips.

5.3.3 Chemical Analysis of Leachate from Laboratory Samples

The detection limit, precision, and concentrations of individual elements for each tire chip size category are shown in Appendix J. Twenty samples were analyzed for each tire chip size range and each sample was analyzed three times to get the average value. Summary results of leachate analysis and the maximum contaminant levels (MCLs), established in EPA CFR 57 (EPA, 1992), are presented in Table 5.5. The leachate was generated under pH = 5 condition. In each tire chip size range, mean and standard deviation are used to depict the data distribution of twenty samples. Only the concentration of barium exceeds the MCLs for the two smaller size ranges (1/4"-1/2" or 7 mm-13 mm and 1/2"-1" or 13 mm-25 mm) of shredded tire material. None of the three tire chip size ranges exceeded MCLs for other elements.

The t-statistic test was used to determine whether there are differences in concentrations of elements between the three different size ranges of shredded tire material used or not. The testing hypothesis and significance level for comparison, p-values, and decisions for distinguishing between any two size ranges are presented in Table 5.6. For the smallest size range of shredded tire (1/4"-1/2"; 7 mm-13 mm), the concentrations of aluminum, iron, manganese, and zinc are lower than for the other two shredded tire size ranges but there are no significant differences between concentrations of

Table 5.5: Results of leachate analyses for leachate prepared in the laboratory.

Elements	Leachate Concentrations (ppm)						MCLs (ppm)
	1/4"-1/2"		1/2"-1"		1"-1.5"		
	mean	Std.*	mean	Std.*	mean	Std.*	
Al	0.064	0.018	0.042	0.012	0.037	0.11	-
Ba	2.93	0.99	2.53	0.86	1.45	0.60	2.00
Ca	1.57	0.48	1.55	0.681	1.34	0.643	-
Cd	0.0036	0.0019	0.0024	0.0013	0.0024	0.0016	0.005
Co	0.0022	0.001	0.0029	0.001	0.0027	0.0011	-
Cr	0.0021	0.0009	0.002	0.0009	0.0021	0.0008	0.1
Cu	0.00091	0.00038	0.00118	0.00077	0.00102	0.00031	1.3
Fe	0.64	0.02	3.01	1.14	4.39	1.88	-
Mn	0.017	0.006	2.34	1.79	2.59	2.3	-
Pb	0.0015	0.0007	0.0028	0.002	0.0026	0.0017	0.015
Zn**	2.17	0.88	5.59	2.19	5.42	2.61	-

* Std. = Standard deviation about the mean for analyzed samples; twenty samples analyzed in each tire size range

** ppm in actual sample; actual solution analyzed was diluted by a factor of 100.

Table 5.6: Results of t-test for leachate analysis to assess the effect of tire size range on the concentration of various elements.

Test Hypotheses: $H_0: \mu_1 = \mu_2$ $H_1: \mu_1 \neq \mu_2$ Critical Value: $\alpha = 0.005$		
Elements	Test Statistic: p-Value	Decision
Al	0 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0.21 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Ba	0.24 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0 ($\mu_B:\mu_C$)	$\mu_A = \mu_B > \mu_C$
Ca	0.91 ($\mu_A:\mu_B$); 0.06 ($\mu_A:\mu_C$); 0.39 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cd	0.03 ($\mu_A:\mu_B$); 0.07 ($\mu_A:\mu_C$); 0.89 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Co	0.47 ($\mu_A:\mu_B$); 0.47 ($\mu_A:\mu_C$); 0.66 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cr	0.48 ($\mu_A:\mu_B$); 0.48 ($\mu_A:\mu_C$); 0.72 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Cu	0.21 ($\mu_A:\mu_B$); 0.37 ($\mu_A:\mu_C$); 0.39 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Fe	0 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0.01 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Mn	0 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0.73 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$
Pb	0.009 ($\mu_A:\mu_B$); 0.005 ($\mu_A:\mu_C$); 0.74 ($\mu_B:\mu_C$)	$\mu_A = \mu_B = \mu_C$
Zn	0 ($\mu_A:\mu_B$); 0 ($\mu_A:\mu_C$); 0.81 ($\mu_B:\mu_C$)	$\mu_A < \mu_B = \mu_C$

A represents 1/2"-1/4"; B represents 1/2"-1"; C represents 1"-1.5"

those elements for the two bigger size ranges of shredded tire. The largest size range of shredded tire (1"-1.5"; 25 mm-38 mm) has a lower concentration of barium than the other two size ranges of shredded tire but there is no significant difference between concentrations of that element for the two smaller size ranges of shredded tire material. The test results show that there is no significant difference among the three size ranges of tire chips for other elements. Thus, the concentrations of leachate released from the smaller size ranges of shredded tire material are not expected to exceed the MCLs as far as concentrations of cadmium, cobalt, chromium, copper, and lead are concerned, but they may exceed the MCLs for barium.

5.3.4 Chemical Analysis of the Leachate from the Field Samples

The pH values of the field samples varied from 6.6 to 7.4 and the temperature varied from 4 °C to 28 °C during the sample collection period. The detection limits, precision, and concentrations of each element, are shown in Appendix K along with the pH values and temperature of the collected samples. The maximum concentrations of the elements, along with the maximum contaminant levels (MCLs) for each element, as established in EPA CFR57 (EPA, 1992), are presented in Table 5.7 and the number of days to achieve these concentrations are presented in Table 5.8.

Among the three size ranges of pure shredded tire, the maximum concentrations of barium are slightly in excess of the MCLs but concentrations of other elements of concern including cadmium, chromium, copper, and lead do not exceed the MCLs. For the elements of iron, manganese, lead, and zinc, leachate samples from the bigger size ranges

Table 5.7: The maximum concentrations of leachate from the field samples placed on the roof:

(a) pure tire

Elements	Leachate Concentrations (ppm)			MCLs (ppm)
	Pure Tire (1/4"-1/2")	Pure Tire (1/2"-1")	Pure Tire (1"-1.5")	
Al	0.44	0.31	0.44	-
Ba	2.84	2.16	2.09	2.00
Ca	45.9	29.7	33.6	-
Cd	0.004	0.003	0.003	0.005
Co	0.11	0.1	0.13	-
Cr	0.09	0.06	0.07	0.1
Cu	0.05	0.02	0.01	1.3
Fe	1.81	7.21	7.5	-
Mn	0.73	3.04	3.38	-
Pb	0.002	0.003	0.007	0.015
Zn	19.57	22.5	32.73	-

(b) soil-tire mixtures

Elements	Leachate Concentrations (ppm)			MCLs (ppm)
	70% silt, 30% Tire (1/4"-1/2")	70% clay, 30% Tire (1/4"-1/2")	40% clay, 60% Tire (1/4"-1/2")	
Al	0.33	0.38	0.32	-
Ba	1.05	0.79	1.97	2.00
Ca	737.58	668.26	280.94	-
Cd	0.003	0.001	0.003	0.005
Co	0.06	0.05	0.04	-
Cr	0.04	0.06	0.04	0.1
Cu	0.01	0	0.04	1.3
Fe	1.24	3.06	2.12	-
Mn	0.45	0.42	0.58	-
Pb	0.0014	0	0.002	0.015
Zn	1.93	6.12	7.65	-

 Insignificant data because it is below the detection limits.

Table 5.8: The length of time, in days, after which the maximum concentrations of various elements were observed in the leachate samples obtained from the field samples placed on the roof:

(a) pure tire

Elements	Time period for maximum concentration of each element (days)		
	Pure Tire (1/4"-1/2")	Pure Tire (1/2"-1")	Pure Tire (1"-1.5")
Al	217	159	217
Ba	444	369	427
Ca	249	112	138
Cd	N/A	N/A	N/A
Co	369	369	398
Cr	N/A	N/A	N/A
Cu	N/A	398	N/A
Fe	520	63	184
Mn	217	249	159
Pb	369	138	217
Zn	398	217	159

(b) soil-tire mixtures

Elements	Time period for maximum concentration of each element (days)		
	70% silt, 30% Tire (1/4"-1/2")	70% clay, 30% Tire (1/4"-1/2")	40% clay, 60% Tire (1/4"-1/2")
Al	457	217	398
Ba	369	427	369
Ca	159	138	159
Cd	N/A	N/A	N/A
Co	138	398	398
Cr	N/A	N/A	N/A
Cu	N/A	N/A	369
Fe	159	184	369
Mn	N/A	398	249
Pb	184	N/A	369
Zn	369	63	138

N/A: no significant concentration was detected

of shredded tire have higher concentrations since the steel contained in the bigger size ranges of tire chips can release more of those elements. The concentration of cobalt is similar among all three size ranges of shredded tire.

For soil-tire mixtures, however, the concentrations do not exceed the MCLs for any of the elements of concern to EPA except the concentration of barium in the leachate from clay-tire mixture containing 40% clay and 60% shredded tire material of 1/4"-1/2" (7 mm-13 mm) size range which is close to the MCLs. The leachate from the silt-tire mixture containing 70% silt and 30% shredded tire material of 1/4"-1/2" (7 mm-13 mm) size range has a higher concentration of barium than the leachate from the clay-tire mixture containing 70% clay and 30% shredded tire material of 1/4"-1/2" (7 mm-13 mm) size range but lower concentrations of iron and zinc. This indicates that the clay soil used can absorb more barium, less iron, and less zinc than the silt soil. The concentrations of aluminum and cobalt are close for all three groups of soil-tire mixtures.

The concentrations of the elements like barium, cobalt, manganese, lead, and zinc, which are higher in the leachate from pure tire material than pure soil (Table 5.7), can be reduced by adding soil to the pure tire shreds. Therefore, the use of soil-tire mixtures in civil engineering applications is environmentally safer than use of shredded tire material alone. The concentration of calcium is much higher for the soil-tire mixtures than for the pure tire material due to the abundance of calcareous material in the silt and clay soils used in this research (United States Department of Agriculture, 1978).

Comparison of different proportions of clay mixed with 1/4"-1/2" (7 mm-13 mm) size

shredded tire material shows that the concentrations of barium, manganese, and zinc decrease with an increase in the proportion of clay. It could be the smaller content of shredded tire or the sorption effect of clay soil which causes the concentrations of these elements to decrease with an increase in the amount of clay soil.

The concentration of leachate sample increased and then decreased after reaching the maximum concentration for each element in all six field samples. The number of exposure days after which the leachate sample had maximum concentration for each element are shown in Table 5.8 for all six field samples (three size ranges of shredded tire and three soil-tire mixtures). The concentrations of barium and copper reached the maximum after exposure for twelve to fourteen months for all three size ranges of shredded tire material and all three soil-tire mixtures. For lead, the exposure days to reach the maximum concentration varied for all three tire sizes and all three soil-tire mixtures during the entire period of exposure.

Based on the results of chemical analyses (Tables 5.7 and 5.8), the pure shredded tire material may release more hazardous material and contaminate the surface water or ground water to a greater extent than soil-tire mixtures, which are likely to have less environmental impact. The pure shredded tire material (<1.5" or <38 mm) releases more hazardous material even when pH ranges from 6.6 to 7.4. However, the concentration of each element released from soil-tire mixtures was below MCLs even though the smallest tire size (1/4"-1/2" or 7 mm-13 mm) was used. This suggests that a soil-tire mixture can be categorized as a non-hazardous material when the proportion of soil is above 40%.

Therefore, the proportion of shredded tire material should not be more than 60% for the practical application.

5.3.5 Chemical Analysis of the Leachate from the Embankment Samples

The pH values of the field samples varied from 6.7 to 7.1 and the temperature varied from 5 °C to 28 °C during the sample collection period. The detection limit, precision, concentration of each element, and pH values and temperature of collected samples, are shown in Appendix L. The maximum concentrations of the elements from leachate samples collected from the test embankment, and the maximum contaminant levels (MCLs) established in EPA CFR57 (EPA, 1992), are presented in Table 5.9 while the days to achieve the maximum concentration are given in Table 5.10. The concentrations of elements of concern (barium, cadmium, chromium, copper, and lead) do not exceed the MCLs. Furthermore, the concentrations of aluminum, barium, cobalt, chromium, iron, manganese, and zinc decrease with increasing depth of sampling. Generally, the leachate collected from greater depths might be expected to have higher concentrations since it was in contact with the shredded tire material for a longer period of time; however, in this case, the concentrations of elements listed above are lower perhaps due to the sorption process of clay soil (Bourg and Gadalia, 1989; Bruno et al., 1989; Kooner, 1993).

After reaching the maximum concentration, the concentrations of various elements in the leachate samples decreased for 1-foot (0.3 m) and 2-foot (0.6 m) depths. The length of time for the maximum concentration of each element to reach are shown in Table 5.10 for all four depths. The concentrations of barium and chromium reached the maximum after

Table 5.9: Results of chemical analysis of the leachate collected from the field embankment.

Elements	Leachate Concentrations (ppm)				MCLs (ppm)
	1-foot depth	2-foot depth	3-foot depth	4-foot depth	
Al*	0.37	0.3	0.01	0	-
Ba	0.07	0.01	0.002	0.002	2.00
Cd	0.0001	0.0002	0	0	0.005
Co	0.005	0.003	0	0	-
Cr	0.006	0.004	0	0	0.1
Cu	0	0	0	0	1.3
Fe*	4.4	4	3.9	3.1	-
Mn**	2.34	2.13	0.44	0.48	-
Pb	0	0.0001	0	0	0.015
Zn*	5.7	4.2	3.9	3.8	-

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100.

** ppm in actual sample; actual solution analyzed was diluted by a factor of 4.

 Insignificant data because it is below the detection limits.

Table 5.10: The length of time, in days, after which the maximum concentrations of various elements were observed in the leachate samples obtained from the embankment.

Elements	Time period for maximum concentration of each element (days)			
	1-foot depth	2-foot depth	3-foot depth	4-foot depth
Al	169	223	N/A	N/A
Ba	223	117	N/A	N/A
Cd	N/A	N/A	N/A	N/A
Co	223	223	N/A	N/A
Cr	223	133	N/A	N/A
Cu	N/A	N/A	N/A	N/A
Fe	223	274	248	248
Mn	117	117	248	248
Pb	N/A	N/A	N/A	N/A
Zn	274	248	248	248

N/A: no significant concentration was detected

seven months for 1-foot (0.3 m) depth and three months for 2-foot (0.6 m) depth. The length of time to reach the maximum concentration of barium and chromium was shorter for the 2-foot (0.6 m) depth than for the 1-foot (0.3 m) depth because of the sorption capacity of clay soil.

The analysis of leachate from the test embankment shows concentrations of barium, cadmium, chromium, copper, and lead to be at levels below the MCLs as specified by EPA in CFR57 (EPA, 1992). The highest concentration is found at the 1-foot (0.3 m) depth which could be less interaction between leachate and the clay soil (i.e. less sorption effect) at that depth. The concentrations of barium and chromium decrease after exposure for seven months, thereby making it possible to predict that the concentrations of barium and chromium will not exceed the MCLs in the future. Overall, based on the data from the test embankment, the clay-tire mixture can be categorized as a non-hazardous material when the proportion of clay soil is 70% or more.

5.4 Discussion

Previous research by Minnesota Pollution Control Agency (MPCA, 1990) and by Black and Shakoor (1994) reveals that the concentrations of some elements in the leachate from pure tire material can exceed the MCLs. For example, the chemical analyses by MPCA (1990) of leachate samples extracted from pure tire material showed that the concentrations of barium, cadmium, chromium, and lead were above MCLs for the worse condition (pH < 3.5). Black and Shakoor (1994) performed chemical analyses of leachate extracted from <1 mm size shredded tire material under pH = 5 condition and reported

concentrations of chromium to be above MCLs. In this research, the concentration of barium released from <1" (25 mm) size shredded tire material was above the MCLs under pH = 5 condition.

Other studies (Grefe, 1989; RMA, 1990; Edil and Bosscher, 1992; Bosscher et al., 1993; Humphrey et al., 1997) have suggested that shredded tire material is not a hazardous material. Grefe (1989) and RMA (1990) analyzed the leachate extracted from pure tire in the laboratory. Edil and Bosscher (1992) and Bosscher et al. (1993) analyzed the leachate collected from a test embankment constructed of pure tire material. They did not find the concentrations of any element to be above the MCLs. In the studies by Grefe (1989) and RMA (1990), the pH of the acid, which they used to extract the leachate from the tire, was above 5.5 and that may be the reason why they could not find the higher concentrations of metals in the leachate. In the studies by Edil and Bosscher (1992) and Bosscher et al. (1993), the range of pH of rain water was 7.1 to 7.7 during their collections. The tire material did not leach much metals owing to the non-acidic conditions. Humphrey et al. (1997) collected groundwater samples from around a tire-chip layer beneath an asphalt concrete pavement and analyzed the concentrations of barium, cadmium, copper, chromium, lead, and selenium released from pure tire chips (25 -300 mm). They concluded that tire chips did not increase the concentration of substances including barium, cadmium, copper, chromium, lead, and selenium in ground water. In this research, none of the concentrations of elements released from the soil-tire mixtures was found to be above the MCLs when the pH ranged from 6.6 to 7.7. These results reveal

that factors which are likely to influence the environmental impact of shredded tire material applications include size of tire chips, proportion of tire chips, and pH value of the surroundings.

The results of chemical analyses from previous research as well as my own research indicate that scrap tire has the potential to leach hazardous material under specific conditions. For concentrations of the elements including barium, cadmium, chromium, copper, and lead not to exceed the MCLs, either scrap tires should be used under non-acidic conditions or they should be mixed with soil to reduce the proportion of shredded tire material and take advantage of the sorption effect of soil. Since the range of pH value of rain water is generally from 3.0 to 7.5 {National Atmospheric Deposition Program (NADP), 1996}, the best way to use shredded scrap tire material for engineering applications is to mix shredded tire material with a fine-grained soil and the amount of soil should be more than 40%. The soil-tire mixtures containing more than 40% soil can be categorized as a non-hazardous material.

Because the sorption capacity of a fine grained soil depends on the clay mineral composition, the criteria about the percentage of soil in soil-tire mixtures, as proposed in this research, should be applied carefully. According to the analysis done by United States Department of Agriculture (1978), the clay soil used in this research consists of illite (30%-40%), vermiculite (6%-10%), chlorite (0%-5%), and kaolinite (0%-5%). Therefore, the 40% of soil content criteria stated above is only suitable for soil which has similar clay mineral composition.

5.5 Summary

The LOI values range from 65.83% to 75.47% with a mean of 70.03% for 1/4"-1/2" (7 mm-13 mm) size tire chips, from 63.49% to 87.18% with a mean of 71.74% for 1/2"-1" (13 mm-25 mm) size tire chips, and from 57.68% to 83.75% with a mean of 70.86% for 1"-1.5" (25 mm-38 mm) size tire chips. The t-test for LOI values shows that there is no significant difference in LOI values between tire sizes and whether or not steel and nylon chords are present in the tire chips.

All chemical analyses were performed by using ICP and GFAA techniques for selected trace metals (aluminum, barium, cadmium, cobalt, chromium, copper, iron, manganese, lead, and zinc). The bulk analyses indicate that pure tire has the potential to contaminate the environment under the worst situation, that is if the tire chips were to degrade completely and all inorganic components were to be released.

The chemical analyses of leachate samples derived in the laboratory show that the concentrations of leachate released from the smaller size ranges (1/4"-1/2", 7 mm-13 mm; 1/2"-1", 13 mm-25 mm) of tire chips may exceed the MCLs for barium under pH = 5 condition. The concentrations of leachate are not expected to exceed the MCLs for other concerned elements including cadmium, chromium, copper, and lead under pH = 5 condition.

The maximum concentrations of the elements from leachate samples collected from the roof decrease from 0.44 ppm, 2.84 ppm, 0.13 ppm, 7.5 ppm, 3.4 ppm, 0.007 ppm, and 32.7 ppm for aluminum, barium, copper, iron, manganese, lead, and zinc, respectively, for

pure tire chips to 0.32 ppm, 0.79 ppm, 0.04 ppm, 1.24 ppm, 0.42 ppm, 0.0014 ppm, and 1.9 ppm for aluminum, barium, copper, iron, manganese, lead, and zinc, respectively, for soil-tire mixtures containing 70% soil. It indicates that the leachate samples from soil-tire mixtures releases less hazardous material, compared to leachate samples from pure shredded tire material, even under acidic conditions.

The maximum concentrations of the elements from leachate samples collected from the test embankment decrease from 0.37 ppm, 0.07 ppm, 0.005 ppm, and 0.006 ppm for aluminum, barium, copper, and chromium, respectively, at 1-foot (0.3 m) depth of the embankment to below detection limits at 4-foot (1.2 m) depth of the embankment. The decrease in concentration reflects the sorption capacity of the clay soil.

The leachate analyses for soil-tire mixtures indicate that less hazardous materials leach from mixtures and that the amount of hazardous material depends on the proportion of soil. Soil-tire mixtures can be categorized as non-hazardous materials when the proportion of soil, containing similar clay mineral content as the soil used in this research, is more than 40%.

CHAPTER 6

ENGINEERING APPLICATIONS OF TIRE-STABILIZED SOILS

Based on the engineering properties and chemical characteristics of soil-tire mixtures described previously, tire-stabilized soils have the potential for the following engineering applications.

6.1 Roadway Embankments

A potential application of soil-tire mixtures can be in the construction of roadway embankments. The Ohio Department of Transportation (ODOT) requires that the maximum dry density of a construction material used for roadway embankments shall not be less than 90 pcf (1.43 Mg/m^3) (ODOT, 1989). The research presented herein shows that soil-tire mixtures containing less than 30% shredded tire material would meet this requirement and, therefore, will be suitable for the construction of roadway embankments. On the basis of environmental considerations, the proportion of shredded tire material should be also no more than 30% for any of the three tire chip sizes (1/4"-1/2" or 7 mm-13 mm; 1/2"-1" or 13 mm-25 mm; and 1"-1.5" or 25 mm-38 mm).

From an economic point of view, since it takes more time to prepare the smaller sizes of shredded tire material, the smaller sizes are more expensive than the larger sizes. Since the largest (1"-1.5" or 25 mm-38 mm) of the three size ranges of shredded tire material used in this study was the cheapest (2 cents/lb), it can be recommended for use in roadway

embankments based on economic considerations alone. However, the soil-tire mixtures with 1"-1.5" (25 mm-38 mm) tire chip size also tend to release more hazardous material than the mixtures with 1/2"-1" (13 mm-25 mm) size material. Therefore, for environmentally safe application of soil-tire mixtures for construction of roadway embankments, the optimum size of shredded tire material appears to be 1/2"-1" (13 mm-25 mm) and the optimum proportion to be about 30%.

6.2 Hydraulic Barriers, Landfill Liners, and Landfill Cover Material

Typically, hydraulic barriers and soil liners for landfills are required to have a permeability value of no more than 2×10^{-6} in/min (10^{-7} cm/sec) (EPA, 1993). The addition of shredded tire material increases the permeability of each of the two soils used. Based on the permeability values obtained in this research, only clay soil mixed with no more than 10% shredded tire material, of any of the three size ranges, and compacted to 95% of maximum dry density and $\pm 2\%$ of optimum water content, is suitable for use as a hydraulic barriers and landfill liners. Since the soil-tire mixtures with bigger tire chip size have higher permeability values and may release more hazardous material, the 1/4"-1/2" (7 mm-13 mm) size shredded tire material is recommended for preparing clay-tire mixtures for use as hydraulic barriers and landfill liners. With less than 10% shredded tire material, the hydraulic barriers and landfill liners would essentially consist of clay but the use of 10% shredded tire material could still significantly reduce the volume of scrap tire material that would normally be buried in the landfill.

The daily landfill cover material should have a permeability of no more than 2×10^{-4}

in/min (10^{-5} cm/sec) (EPA, 1993). Both silt and clay meet this criteria when they are mixed with up to 20% shredded tire material of any of the three size ranges. Therefore, a substantial amount of shredded scrap tire can be utilized as a landfill cover material, providing it is mixed with soils. In order to use soil-tire mixtures for daily landfill cover, the proportion of the shredded tire material should be no more than 20% and the size of the shredded tire material should not be smaller than 1/4" (7 mm). The optimum tire chip size may be 1/2"-1" (13 mm-25 mm) as this size range is less expensive to prepare and results in appropriate permeability.

The environmental impact of leachate chemistry from the shredded scrap tire should be considered in the applications described above. The results of chemical analysis in this research show that the concentrations of heavy metals in the leachate are below the maximum contaminant levels only when the soil-tire mixtures contain less than 30% shredded tire material or more than 70% soil having similar mineral composition as the soils used in this research. Based on the specific requirements (EPA, 1993) and environmental considerations, the maximum recommended proportion of shredded tire material is 20% for all three tire chip sizes (1/4"-1/2" or 7 mm-13 mm; 1/2"-1" or 13 mm-25 mm; and 1"-1.5" or 25 mm-38 mm). The smaller size (1/4"-1/2" or 7 mm-13 mm) of shredded tire material is more desirable due to the smaller increase in permeability for a given proportion, but 1/2"-1" (13 mm-25 mm) or 1"-1.5" (25 mm-38 mm) size material would be more economical.

6.3 Football Fields and Playgrounds

Permeable and non-deformable soils that allow easy growth of grass are required for construction of football fields and playgrounds. Since the addition of shredded tire material increases the permeability and shear strength of soil-tire mixtures for tire chip sizes of 1/2"-1" (13 mm-25 mm) and 1"-1.5" (25 mm-38 mm), it is believed that soil-tire mixtures are well suited for construction of football fields and playgrounds. Because of environmental considerations, the maximum proportion of shredded tire material should be no more than 30%, and the 1/2"-1" (13 mm-25 mm) size material would be more desirable than 1"-1.5" (25 mm-38 mm) size material due to lower concentrations of heavy metal in the leachate released from 1/2"-1" (13 mm-25 mm) size material.

Applications of pure shredded tire material in making football fields have already been practiced on a trivial basis in such states as Colorado, Michigan, and Pennsylvania where each football field consumed as many as 12,000 scrap tire chips (BioCycle, 1990). However, no specific information is available on the use of soil-tire mixtures for such applications. Since soil-tire mixtures are environmentally safer than pure tire chips, and since their engineering properties meet the requirements of football fields and playgrounds, it is believed that soil-tire mixtures are a better material to construct football fields and playgrounds than pure tire chips.

6.4 Lightweight Fill Material

Both the stability and settlement behavior of embankments on soft foundations, such as clay and peat, can be improved by the use of lightweight fill material. The requirements of a lightweight fill material include low density, high shear strength, and good drainage

characteristics. Since the addition of shredded tire material was found to decrease the maximum dry density, increase the permeability, and improve the strength characteristics, such usage seems warranted.

Soil-tire mixtures can also be used to reconstruct already failed, or potentially unstable, slopes. The driving force responsible for slope movement can be lowered by reducing the weight of the soil mass behind the slope. As mentioned previously, soil-tire mixtures exhibit low densities, good drainage characteristics, and improved strength characteristics. Because of these desirable characteristics, soils stabilized with shredded scrap tire material should be quite suitable for reconstruction of unstable slopes.

A retaining wall must be designed to withstand the driving force to prevent the failure of a steep slope in a low strength soil such as clay. When the soil behind a retaining wall has poor drainage characteristics, the wall has to face not only the soil pressure but also the lateral pressure of water. This necessitates building larger retaining walls, incurring increased costs as a result. Since soil-tire mixtures are characterized by high permeability and low density values, an alternative way is to excavate the soil comprising the slope, mix it with shredded tire material, and replace as a backfill material for the retaining wall. This method can produce an economical and structurally sound design. In case of relatively gentler ($< 35^\circ$) slopes, less than 30 feet (9 m) high, no retaining wall is considered necessary.

Although this research showed that about 50% shredded tire material needs to be added to the soil to convert it to a truly lightweight fill material (density reduced to two

third of the density of soil alone), a semi-lightweight fill material can be prepared at 30% tire content. At 30% tire content, the shear strength was found to improve for both 1/2"-1" (13 mm-25 mm) and 1"-1.5" (25 mm-38 mm) size ranges. The results of chemical analysis indicate that the soil-tire mixtures do not have a significant environmental impact when the proportion of soil used in this research is more than 70%. However, since the smaller of these two size ranges releases less hazardous material, it is recommended for use as lightweight fill material. Thus, based on the environmental and economic considerations as well as engineering properties, it is recommended that 30% of 1/2"-1" (13 mm-25 mm) size shredded tire material should be used to prepare soil-tire mixtures for use as a lightweight fill material.

Applications of pure tire chips as a lightweight fill material for highway embankments have been practiced in Minnesota and Oregon (Read et al., 1991; Upton and Machan, 1993), and as a lightweight backfill material for retaining walls in Maine (Humphrey et al., 1997). However, no specific information is available about using soil-tire mixtures for similar applications. As stated previously, the adverse impact of soil-tire mixtures on the environment is much less and their engineering properties are significantly better than pure tire chips. Therefore, the soil-tire mixtures are considered more suitable for applications as a lightweight fill material than pure tire chips.

6.5 Economic Evaluation

In order to evaluate the economic feasibility of use of soil-tire mixtures for construction purposes, the unit prices of soil-tire mixtures and the other construction

materials are presented in Table 6.1. The prices of soil-tire mixtures are higher than other construction materials. The indirect costs of mixing soil with shredded tire material would further add to the expenses. However, the prices of soil-tire mixtures can be reduced by increased application and large scale production of shredded tire material in future. Therefore, the utilization of soil-tire mixtures as a construction material could become a feasible option from an economic point of view with increased usage.

Table 6.1: Cost comparison of soil-tire mixtures and other construction materials.

Material	Price (\$ / ton)
Silt Soil	1.35
Silt with 10% 1/4"-1/2" Shredded Tire Material	6.12
Silt with 20% 1/4"-1/2" Shredded Tire Material	10.88
Silt with 30% 1/4"-1/2" Shredded Tire Material	15.65
Silt with 10% 1/2"-1" Shredded Tire Material	5.12
Silt with 20% 1/2"-1" Shredded Tire Material	8.88
Silt with 30% 1/2"-1" Shredded Tire Material	12.65
Silt with 10% 1"-1.5" Shredded Tire Material	4.42
Silt with 20% 1"-1.5" Shredded Tire Material	7.48
Silt with 30% 1"-1.5" Shredded Tire Material	10.55
Clay Soil	3.15
Clay with 10% 1/4"-1/2" Shredded Tire Material	7.74
Clay with 20% 1/4"-1/2" Shredded Tire Material	12.32
Clay with 30% 1/4"-1/2" Shredded Tire Material	16.91
Clay with 10% 1/2"-1" Shredded Tire Material	6.74
Clay with 20% 1/2"-1" Shredded Tire Material	10.32
Clay with 30% 1/2"-1" Shredded Tire Material	13.91
Clay with 10% 1"-1.5" Shredded Tire Material	6.04
Clay with 20% 1"-1.5" Shredded Tire Material	8.92
Clay with 30% 1"-1.5" Shredded Tire Material	11.81
Gravel	2.45
Sand	2.65
Slag	12
Fly Ash	15
Bottom Ash	10

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The conclusions of this research can be summarized as follows:

1. The maximum dry density decreases linearly with an increase in shredded tire content for both soil types and all three sizes of tire chips used in this study. For silt-tire mixtures, the maximum dry density decreases from 107 pcf (1.70 Mg/m^3) for pure silt to nearly 53 pcf (0.85 Mg/m^3) at 90% shredded tire content for all three sizes of tire chips. For clay-tire mixtures, the maximum dry density decreases from 103 pcf (1.65 Mg/m^3) for pure silt to nearly 55 pcf (0.88 Mg/m^3) at 90% shredded tire content for all three sizes of tire chips. For both soil-tire mixtures, the maximum dry density values are reduced to $2/3$ of the values for soils alone at approximately 50% tire content indicating that a lightweight fill material can be produced by mixing 50% soil with 50% shredded tire material by weight. At shredded tire content less than 50% (e.g. 30%), a semi-lightweight fill can be produced.
2. The optimum water content decreases only slightly from 15% for pure silt soil and 16% for pure clay soil to 14% at 50% shredded tire content for both soil-tire mixtures beyond which it shows a rapid decrease from 14% to less than 8% at 90% tire content for both soil types and all three tire sizes used.

3. The permeability of soil-tire mixtures was found to increase by six orders of magnitude from 2×10^{-6} in/min (10^{-7} cm/sec) at 10% shredded tire content to 2×10^{-1} in/min (10^{-2} cm/sec) at 40% shredded tire content for both soil types and all three sizes of tire chips. Beyond 40% tire content, the permeability of the mixtures increases only slightly from 2×10^{-1} in/min (10^{-2} cm/sec) to 2 in/min (10^{-1} cm/sec) at 10% shredded tire content for both soil types and all three sizes of tire chips.
4. For silt-tire mixtures, the friction angle increases from 30° for pure silt soil to 36° at 30% shredded tire content for all three sizes of tire chips. For clay-tire mixtures, however, the friction angle increases from 35° for pure clay soil to 38° at 20% shredded tire content, and then decreases to 31° at 30% shredded tire content for all three sizes of tire chips. Therefore, if improvement of the friction angle is the main concern, the amount of shredded tire material should not exceed 20% in clay-tire mixtures.
5. The cohesion values of soil-tire mixtures decrease to half of the cohesion values for original soils [1656 psf (79 KN/m^2) for silt and 2635 psf (126 KN/m^2) for clay] at 30% shredded tire content of 1/4"-1/2" (7 mm-13 mm) size range. For soil-tire mixtures containing the other two sizes of tire chips, the cohesion increases to 2800 psf (134 KN/m^2) for silt-tire mixtures and 3000 psf (144 KN/m^2) for clay-tire mixtures at 10% shredded tire content by weight, and then drops to 2400 psf (115 KN/m^2) for silt-tire mixtures and 2700 psf (129 KN/m^2) for clay-tire mixtures at 30% shredded tire content.

6. The unconfined compressive strength decreases with an increase of shredded tire content for both soil types and all three size ranges of shredded tire. For silt-tire mixtures, the unconfined compressive strength decreases from 4077 psf (195 KN/m²) for pure silt soil to zero at about 50% shredded tire content for all three sizes of tire chips. For clay-tire mixtures, the decrease in unconfined compressive strength is from 6600 psf (316 KN/m²) for pure clay to zero at about 80% shredded tire content for the two smaller sizes (1/4"-1/2", 7 mm-13 mm and 1/2"-1", 13 mm-25 mm) of tire chips, and zero at 40% shredded tire content for the 1"-1.5" (25 mm-38 mm) size tire chips. At higher shredded tire content (> 50% for silt-tire mixtures and > 60% for clay-tire mixtures), the unconfined compressive strength of soil-tire mixtures is almost zero, which implies that silt-tire mixtures containing more than 50% shredded tire content and clay-tire mixtures containing more than 60% shredded tire content should be used only behind some form of retaining structures.
7. The compression index values for the two soil types (0.05 for silt soil and 0.10 for clay soil) are doubled at 30% shredded tire content for all three sizes of tire chips, implying that settlement will increase with increasing shredded tire content.
8. The degradation values of shredded tire material upon exposure to climatic conditions are 2.34%, 3.28%, and 5.41% for 1/4"-1/2" (7 mm-13 mm) size of tire chips, 1/2"-1" (13 mm-25 mm) size of tire chips, and 1"-1.5" (25 mm-38 mm) size of tire chips, respectively. The degradation of shredded tire material increases from 5.41% for pure tire chips to 10.97% for clay-tire mixtures containing 30% shredded

tire content of 1/4"-1/2" (7 mm-13 mm) size range and 11.17% for silt-tire mixtures 30% shredded tire content of 1/4"-1/2" (7 mm-13 mm) size range. This suggests that the smaller tire chips and the higher soil proportion result in higher amount of tire degradation because of the higher surface area of tire chips exposed to microorganism attack.

9. The rototiller appears to be the most appropriate means of mixing soil and tire chips in construction projects involving soil-tire mixtures. Also, the sheepsfoot roller is quite suitable for mixing and compacting the soil-tire mixtures.
10. Results of settlement survey show that most of the crest settlement (6" or 15 cm) of the test embankment occurred during the first four months after which the rate of settlement slowed down significantly. The slope angles of both sides of the test embankment were found to be almost constant with time.
11. Two equations were derived for quick determination of the factor of safety values against slope failure for embankments made of soil-tire mixtures containing 70% clay and 30% shredded tire material, by weight, and having different heights and slope angles. Based on these equations, the test embankment was found to have a factor of safety of 4.1 under dry conditions and of 2.1 under saturated conditions.
12. The bulk analyses as well as the leachate analyses indicate that pure tire chips have the potential to contaminate the environment under the worst situation, that is if the tire chips were to degrade completely and all inorganic components were to be released.

13. The chemical analyses of leachate samples prepared in the laboratory show that the concentrations of leachate released from the smaller size ranges (1/4"-1/2", 7 mm-13 mm; 1/2"-1", 13 mm-25 mm) may exceed the MCLs for barium under pH = 5 condition. The concentrations of leachate are not expected to exceed the MCLs for other concerned elements including cadmium, chromium, copper, and lead under pH = 5 condition.
14. The maximum concentrations of the elements from leachate samples collected from the field showed a decrease from 0.44 ppm, 2.84 ppm, 0.13 ppm, 7.5 ppm, 3.4 ppm, 0.007 ppm, and 32.7 ppm for aluminum, barium, cobalt, iron, manganese, lead, and zinc, respectively, for pure tire chips to 0.32 ppm, 0.79 ppm, 0.04 ppm, 1.24 ppm, 0.42 ppm, 0.0014 ppm, and 1.9 ppm for aluminum, barium, cobalt, iron, manganese, lead, and zinc, respectively, for soil-tire mixtures containing 70% soil. This indicates that the leachate samples from soil-tire mixtures release less hazardous material, compared to leachate samples from pure shredded tire material, even under acidic conditions.
15. The maximum concentrations of the elements from leachate samples collected from the test embankment decrease from 0.37, 0.07, 0.005, and 0.006 for aluminum, barium, cobalt, and chromium, respectively, at 1-foot depth of the embankment to below detection limits at 4-foot depth of the embankment. This reflects the sorption capacity of the clay soil.
16. Soil-tire mixtures can be categorized as non-hazardous materials when the

proportion of soil, of similar clay mineral compositions as the clay soil used in this research, is more than 40%.

7.2 Recommendations for Future Research

1. In order to better document the environmental impact of soil-tire mixtures, the amounts and types of heavy metal in the leachate from soil-tire mixtures should be evaluated for a longer period. In addition, a thorough and detailed chemical evaluation of the soil samples extracted from soil-tire mixtures should be performed to investigate the changes that occur in soil chemistry with time.
2. A pilot field study should be performed to evaluate the settlement and stability behavior of soil-tire mixtures in roadway embankments under actual traffic loads.

REFERENCES

- Ahmed, I., 1992, Laboratory study on properties of rubber soils: Report No. FHWA/IN/JHRP-91/3, School of Civil Engineering, Purdue University, West Lafayette, Indiana, 145p.
- American Society for Testing and Materials, 1993, Soil and rock, building stones, geotextiles: Annual Book of ASTM Standards, Vol. 4.08, Philadelphia, Pennsylvania, 1467p.
- BioCycle, 1990, New sports fields from old tires: July, 1990 Issue, Vol. 31, No. 7, J.G. Press, Inc., Emmaus, Pennsylvania, 44p.
- BioCycle, 1991, What is the future for rubberized asphalt: April, 1991 Issue, Vol. 32, No. 4, J.G. Press, Inc., Emmaus, Pennsylvania, pp.63-65.
- Black, B.A. and Shakoor, A., 1994, A geotechnical investigation of soil-tire mixtures for engineering applications: Proceedings 1st International Congress on Geotechnics of Waste Materials, Edmonton, Canada, pp.617-623.
- Bosscher, P.J., Edil, T.B. and Eldin, N., 1993, Construction and performance of a shredded waste-tire embankment: Transportation Research Record No. 1345. Transportation Research Board, Washington, D.C., pp.44-52.
- Bourg, A.C.M. and Gadalia, A., 1989, Adsorption of cadmium on soils, kinetics and reversibility: Water-Rock Interaction, Miles, D.L. (ed.), A.A.Balkema, pp.111-116.
- Brand, B., 1974, Scrap tire utilization in road dressings: EPA Report 670-2-74-014, Cincinnati, Ohio, 134p.
- Bressette, T., 1984, Used tire material as an alternative permeable aggregate: Report No. FHWA/CA/TL-84/07, Office of Transportation Laboratory, California Department of Transportation, Sacramento, California, 23p.
- Bruno, J., Carrol, S., Sandino, A., Charlet, L., Karthein, R. and Wersin, P., 1989, Adsorption, precipitation and co-precipitation of trace metals on carbonate minerals at low temperatures: Water-Rock Interaction, Miles, D.L. (ed.), A.A.Balkema, pp.121-124.

- Cadle, S.H. and Williams, R.L., 1980, Environmental degradation of tire-wear particles: Rubber Chemistry and Technology, Vol. 53, No. 4. pp.903-914.
- Cleary, T.M. and Clark, W.H., 1973, Old tires contribute to thruway maintenance: Public Works Magazine, July, 1973, pp.68-70.
- Dahl, P.S., 1990, A PC and LOTUS based data acquisition/reduction system for an ICP spectrometer: Computers & Geosciences, Vol. 16, No. 7, pp.881-896.
- Edil, T.B. and Bosscher, P.T., 1992, Development of engineering criteria for shredded waste tires in highway applications, final report: Research Report, GT-92-9, Wisconsin Department of Transportation, Madison, Wisconsin, 86p.
- Edil, T.B., Bosscher, P.T., and Eldin, N.N., 1990, Development of engineering criteria for shredded or whole tires in highway applications: Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Wisconsin, 19p.
- Eldin, N.N. and Senouci, A.B., 1993, Rubber-tire particles as concrete aggregate: Journal of Materials in Civic Engineering, Vol. 5, No. 4, pp.478-496.
- Environmental Protection Agency (EPA), 1990, Federal Register, 40 CFR, No. 61, Washington, D.C., pp.11798-11877.
- Environmental Protection Agency (EPA), 1991, Markets for scrap tires: Report No. EPA/530-SW 90-074A, Office of Solid Waste, Washington, D.C., 115p.
- Environmental Protection Agency (EPA), 1992, Federal Register, 57 CFR, No. 246, Washington, D.C., 60848p.
- Environmental Protection Agency (EPA), 1993, Federal Register, WAC 173-351-300, Washington, D.C., 87p.
- Foose, G.J., Benson, C.H. and Bosscher, P.J., 1996, Sand reinforced with shredded waste tires: Journal of Geotechnical Engineering, Vol. 122, No. 9, pp.760-767.
- Goddard, H.C., 1975, An economic evaluation of technical systems for scrap tire recycling: EPA Report 600/5-75-019, Cincinnati, Ohio, 38p.
- Grefe, R.T., 1989, Review of the waste characterization of shredded tires: Correspondence/Memorandum, File Ref. 4410-1, Wisconsin Department of Natural Resources, Wisconsin, 105p.

- Hemphill, T.A., 1990, A road of opportunities: Scrap Processing And Recycling, Vol. 47, pp.75-81.
- Holland, G.W., Hu, B. and Smith, M.A., 1993, Identifying composition of tire rubber: Rubber & Plastics News, Vol. 23, No. 9, pp.17-20.
- Holtz, R.D. and Kovacs, W.D., 1981, An introduction to geotechnical engineering: Prentice Hall, Englewood Cliffs, New Jersey, 733p.
- House Bill S2462, 1990, Scrap tire management and recycling opportunities: Committee on Small Business, U.S. House of Representatives, Washington, D.C.
- Hudson, J.F. and Lake, E.E., 1977, A planning bibliography on tire refuse and disposal: EPA Report 68-01-4362, Office of Solid Waste Management Programs, U.S. Environmental Protection Agency, Washington, D.C., 217p.
- Humphrey, D.N., Cosgrove, T., Whetten, N.L. and Hebert, R., 1997, Tire chips reduce lateral earth pressure against the walls of a rigid frame bridge: Proceeding of the Conference on Renewal, Rehabilitation and Upgrades in Civil and Environmental Engineering, 1997 Maine Section ASCE Technical Seminar, 11p.
- Humphrey, D.N., Katz, L.E. and Blumenthal, M., 1997, Water quality effects of tire chips fills placed above the groundwater table: Testing Soil Mixed with Waste or Recycled Materials, ASTM STP 1275, Wasemiller, M.A. and Hoddinott, K.B., (Eds.), American Society for Testing and Materials, pp.299-313.
- Instrumentation Laboratory, 1982, Inductively coupled plasma: Instrumentation Laboratory Inc., Andover, MA, pp.260-308.
- Jones, P.H., Prasad, D., Heskins, M., Morgan, M.H. and Guillet, J.E., 1974, Biodegradability of photodegraded polymers: Environmental Science & Technology, Vol. 8, No. 10, pp.919-921.
- Kooner, Z.S., 1993, Comparative study of adsorption behavior of copper, lead and zinc onto goethite in aqueous systems: Environmental Geology, Vol. 21, No. 4, pp.242-250.
- Kovac, F.J., 1978, Tire Technology: The Goodyear Tire & Rubber Company, 159p.
- Kowalski, T. and Ross, N., 1975, How to build a floating scrap tire breakwater: NOAA Report 76020901, Washington, D. C., 35p.

- Lamb, R., 1992, Using shredded tires as lightweight fill material for road subgrades: Draft Report, Materials and Research Laboratory, Minnesota Department of Transportation, Maplewood, Minnesota, 30p.
- Metcalfe, E., 1987, Atomic absorption and emission spectroscopy: John Wiley & Sons, New York, NY, 289p.
- Minnesota Pollution Control Agency (MPCA), 1990, Waste tires in subgrade road beds: Minnesota Pollution Control Agency, St. Paul, Minnesota, 34p.
- Moats, E.R., 1976, Goodyear Tire-Fired Boiler: Resource Recovery and Conservation, Part I, Akron, Ohio, 11p.
- Morton, M., 1977, Rubber Chemistry: Reinhold Co., New York, NY, 8p.
- National Atmospheric Deposition Program (NADP), 1996, NADP annual data summary: precipitation chemistry in Ohio. National Atmospheric Deposition Program, 117p.
- New York State Department of Transportation (NYSDOT), 1990, Use of scrap rubber in asphalt pavements-a report to the governor and legislature: New York State Department of Transportation, Albany, New York, 12p.
- Ohio State Department of Transportation (ODOT), 1989, Construction and material specifications: Ohio State Department of Transportation, Columbus, Ohio, 674 p.
- Perkin-Elmer, 1985, Techniques in Graphite Furnace Atomic Absorption Spectrophotometer: Part No. 0993-8150. Perkin-Elmer Corp. Ridge field, CT, 224p.
- Read, J., Dodson, T. and Thomas, J., 1991, Experimental project: use of shredded tires for lightweight fill: Federal Highway Administration Report DTFH-71-90-501-OR-11. Federal Highway Administration, Washington, D.C., 13p.
- Rubber Manufacturers Association (RMA), 1990, Scrap tire use, disposal study: RMA Scrap Tire Management Council Report, RMA, Washington, D.C., 28p.
- Scrap Tire Management Council, 1997, Scrap tire use/disposal study: Scrap Tire Management Council, Washington, D.C., 26p.
- Stephens, J.E. and Mokrzewski, 1974, The effect of reclaimed rubber on bituminous mixtures: Report CE74-75, Department of Civil Engineering, University of Connecticut, Storrs, Connecticut, 22p.

- Stone, R.B., Buchanan, C.C., and Steimle, F.W. Jr., 1974, Scrap tires as artificial reefs: Report SW-119, U.S. Environmental Protection Agency, Washington, D.C., 115p.
- Taggart, R.H., 1975, Shredded tires as an auxiliary fuel: General Motors Technical Center, Detroit, Michiga, 12p.
- Tuan, C.H., 1988, Study on the gully control by used-tire structure in northern Taiwan: Proceedings of the International Symposium on Landslides, Vol. 5, pp.1001-1006.
- United States Department of Agriculture, 1978, Soil Survey of Portage County, Ohio: United States Department of Agriculture, Soil Conservation Service, 113p.
- Upton, R.J., and Machan, G.M., 1993, Use of shredded tires for lightweight fill: Oregon Department of Transportation, Salem, Oregon, 32p.
- Whetten, N., Weaver, J., Humphrey, D.N. and Sanford, T., 1997, Rubber meets the road in Maine: Civil Engineering, Vol. 67, No. 9, pp.60-63.

APPENDIX A

RESULTS OF COMPACTION TESTS

Table A-1: Maximum dry density and optimum water content for silt and clay soils.

Soil Type	Maximum Dry Density (pcf)	Optimum Water Content (%)
Silt	106	15.7
Clay	103	16.8

Table A-2: Maximum dry density and optimum water content for three different tire sizes.

Shredded Tire Size	Maximum Dry Density (pcf)	Optimum Water Content (%)
1/4"-1/2"	43	3.2
1/2"-1"	43	3.6
1"-1.5"	44	3.7

Table A-3: Maximum dry density and optimum water content for silt-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Maximum Dry Density (pcf)	Optimum Water Content (%)
1/4"-1/2"	10	99	15.0
	20	94	14.6
	30	87	14.7
	40	80	14.5
	50	77	14.6
	60	71	14.5
	70	62	14.7
	80	53	7.3
	90	48	5.1
1/2"-1"	10	100	14.6
	20	93	14.5
	30	87	14.3
	40	79	13.9
	50	77	14.
	60	70	13.7
	70	63	12.1
	80	54	6.6
	90	48	5.2
1"-1.5"	10	101	14.7
	20	94	14.4
	30	85	14.3
	40	81	14
	50	75	14.1
	60	71	14
	70	63	11.9
	80	53	6.3
	90	48	4.8

Table A-4: Maximum dry density and optimum water content for clay-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Maximum Dry Density (pcf)	Optimum Water Content (%)
1/4"-1/2"	10	96	16.4
	20	92	16.4
	30	84	15.8
	40	81	15.4
	50	75	15.1
	60	72	14
	70	66	12.3
	80	56	9.7
	90	52	5.8
1/2"-1"	10	94	16.1
	20	89	15.7
	30	84	14.6
	40	77	13.6
	50	74	12.3
	60	68	12
	70	63	11
	80	55	8.6
	90	50	4.9
1"-1.5"	10	95	16.1
	20	91	15.3
	30	85	14.8
	40	80	13.8
	50	74	12.6
	60	68	11.9
	70	64	10.5
	80	55	7.9
	90	51	5.0

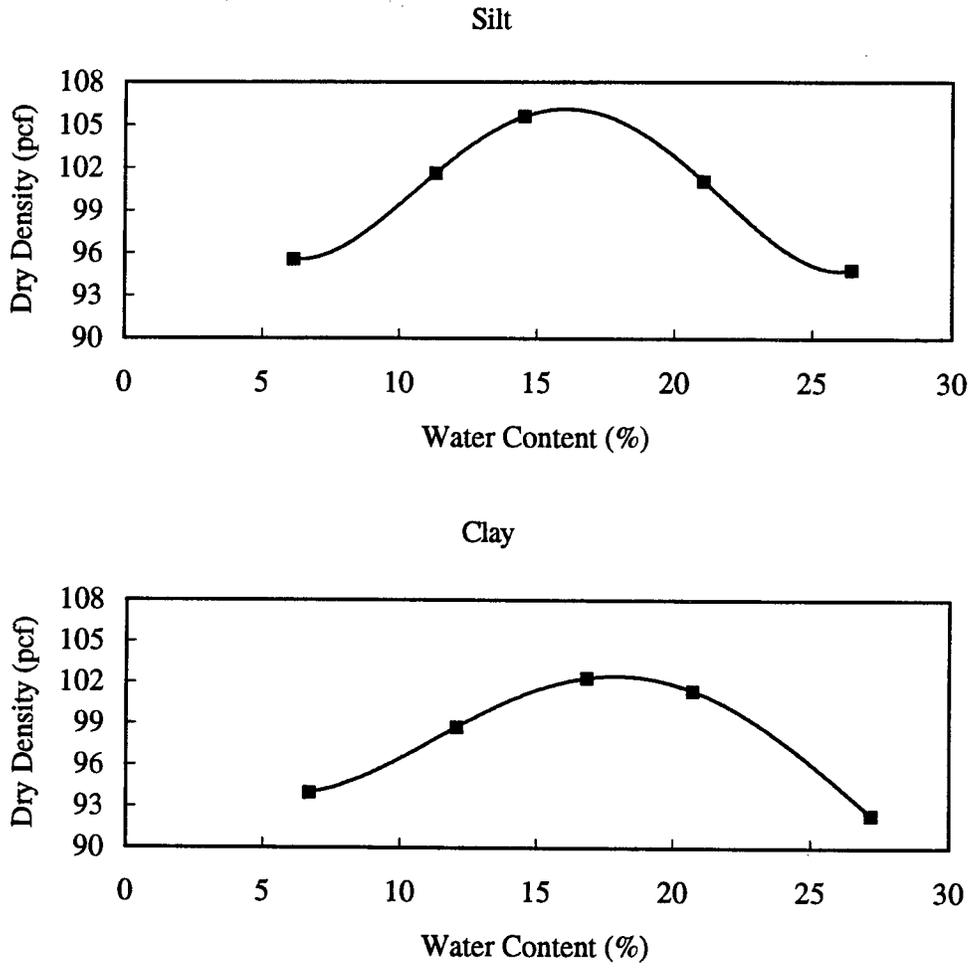
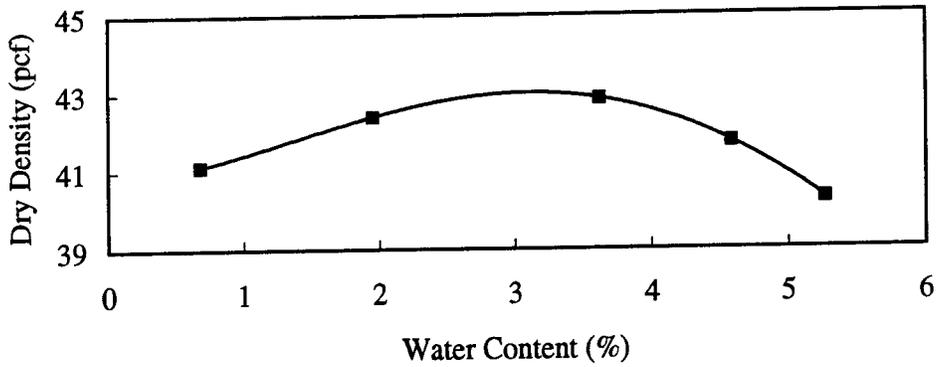
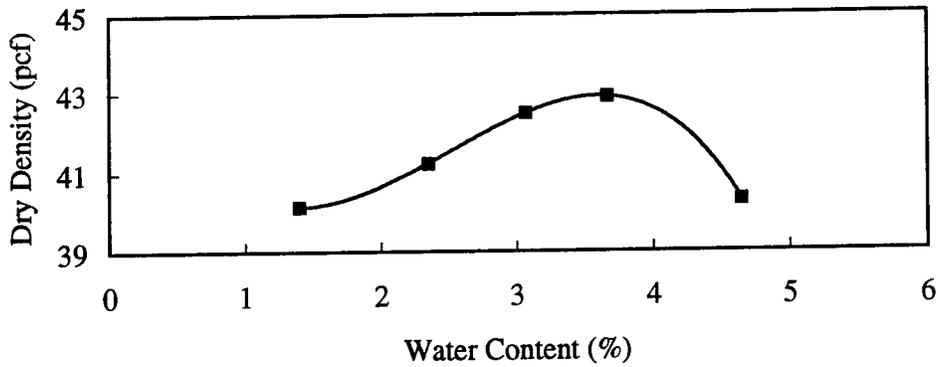


Figure A-1: Compaction curves for pure silt and clay soils.

1/4"-1/2" Shredded Tires



1/2"-1" Shredded Tires



1"-1.5" Shredded Tires

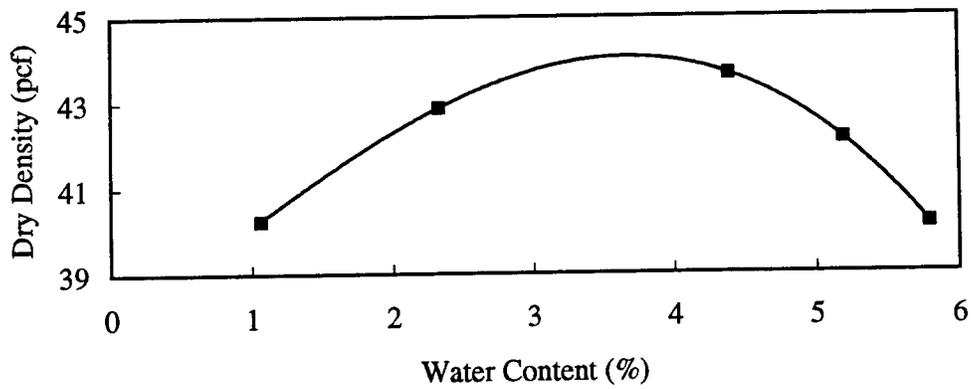


Figure A-2: Compaction curves for shredded tire material.

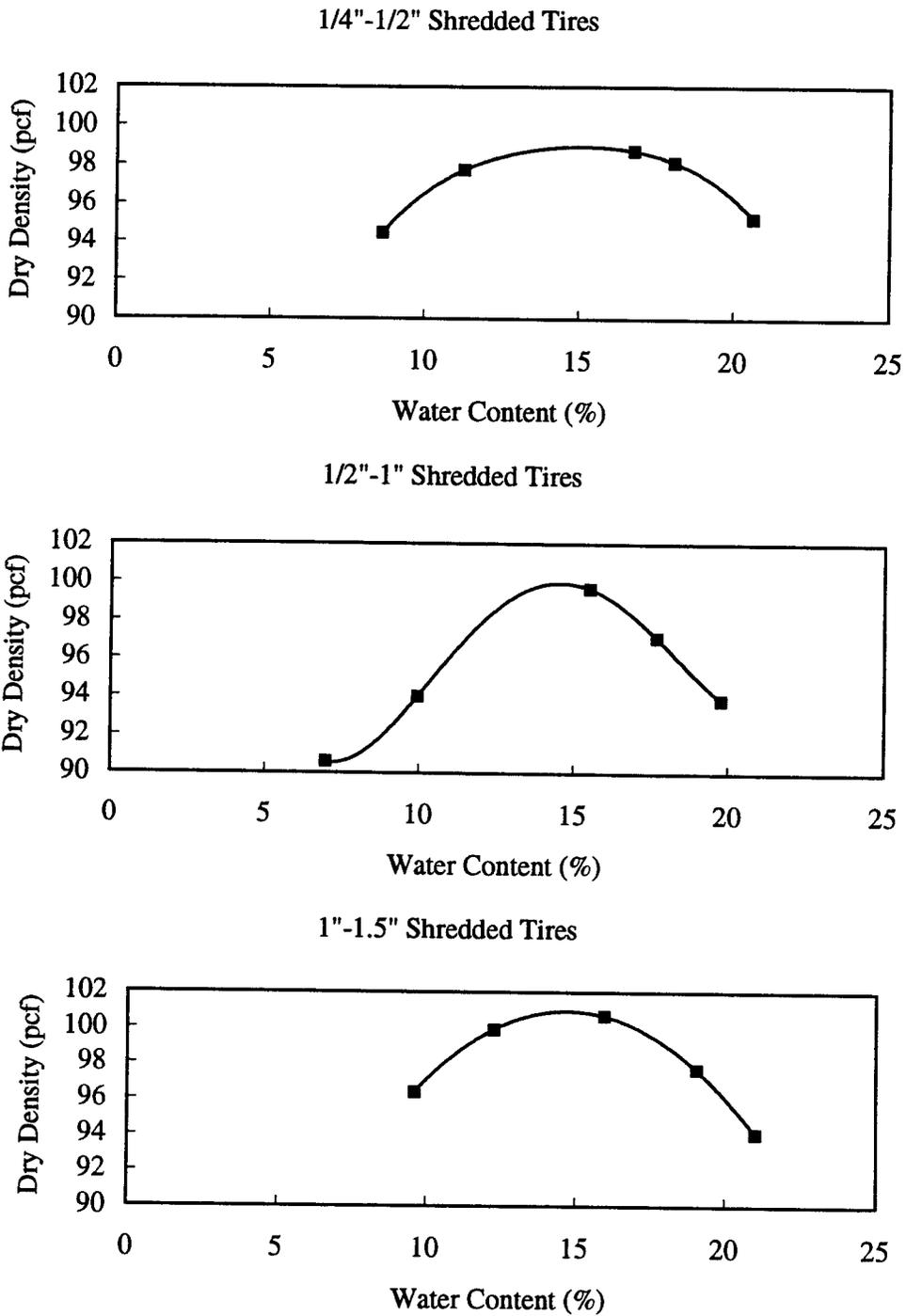


Figure A-3: Compaction curves for silt mixed with 10% shredded tire material.

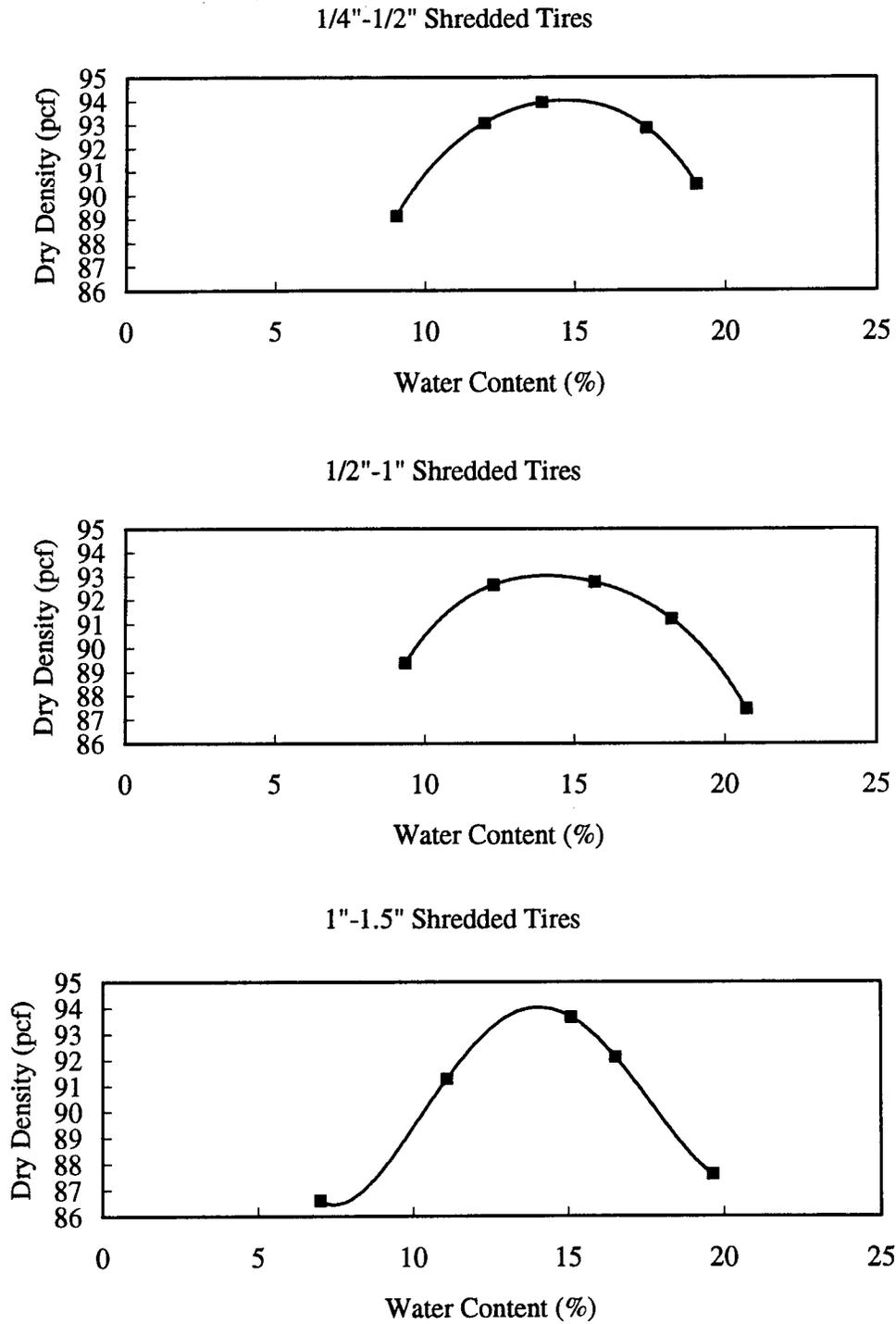


Figure A-4: Compaction curves for silt mixed with 20% shredded tire material.

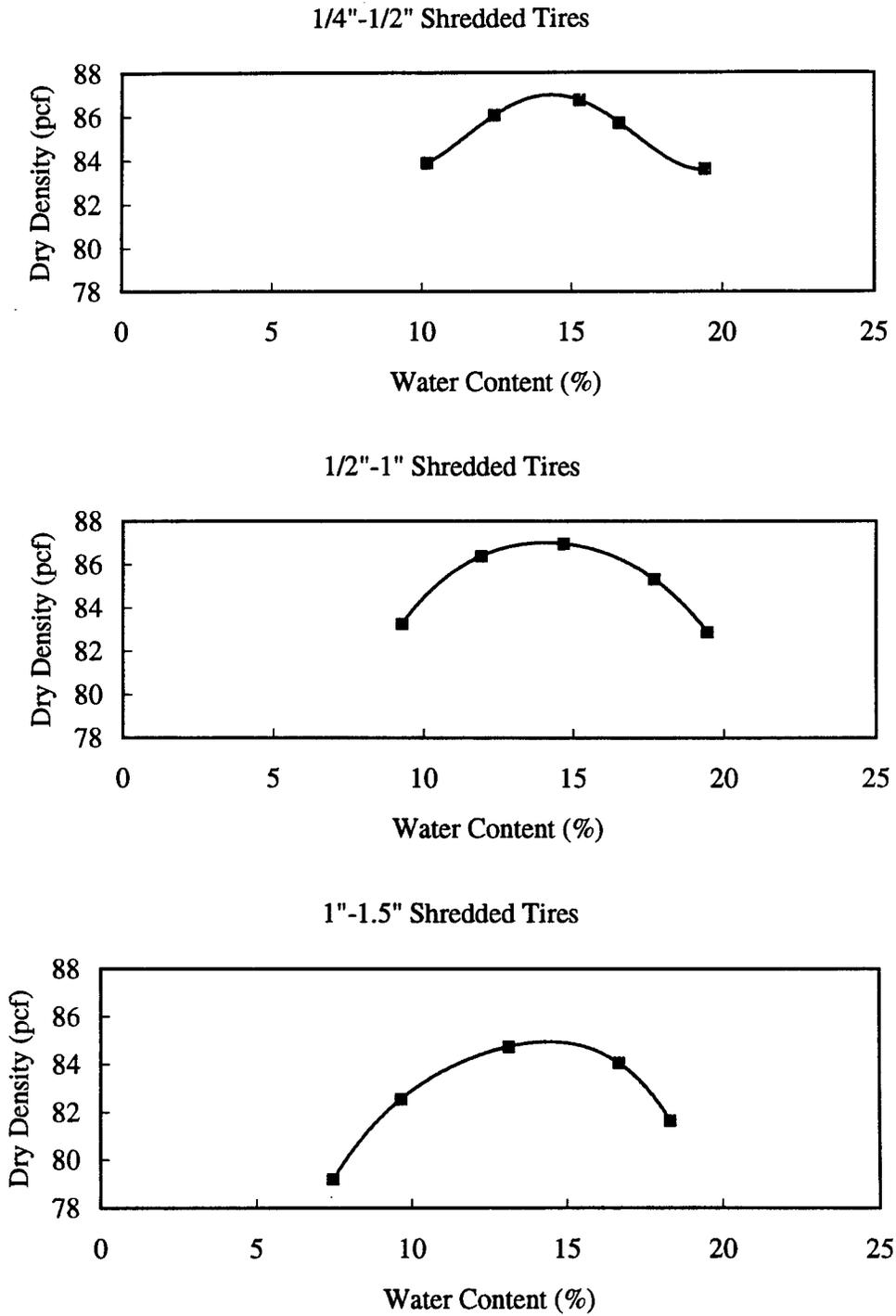


Figure A-5: Compaction curves for silt mixed with 30% shredded tire material.

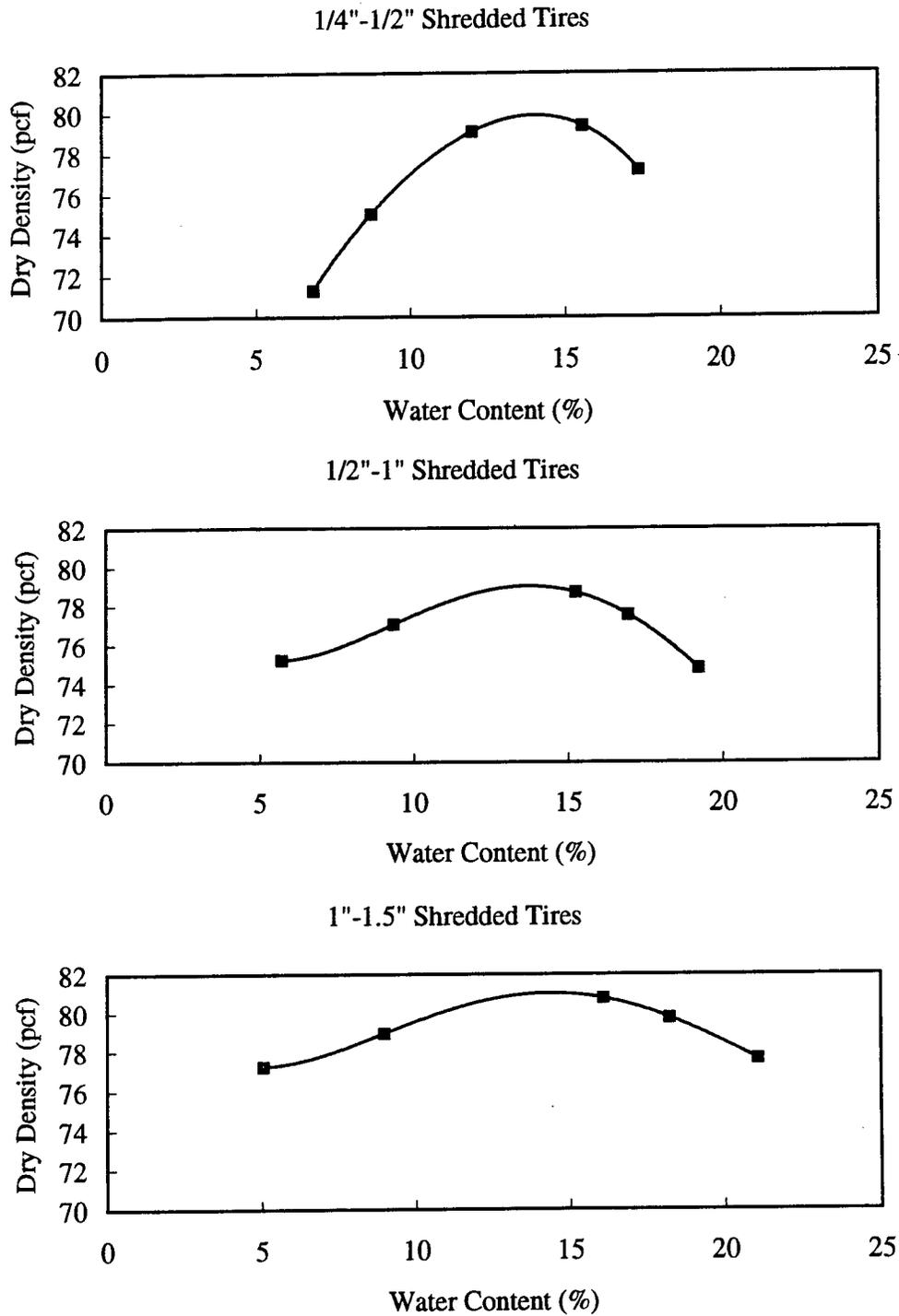


Figure A-6: Compaction curves for silt mixed with 40% shredded tire material.

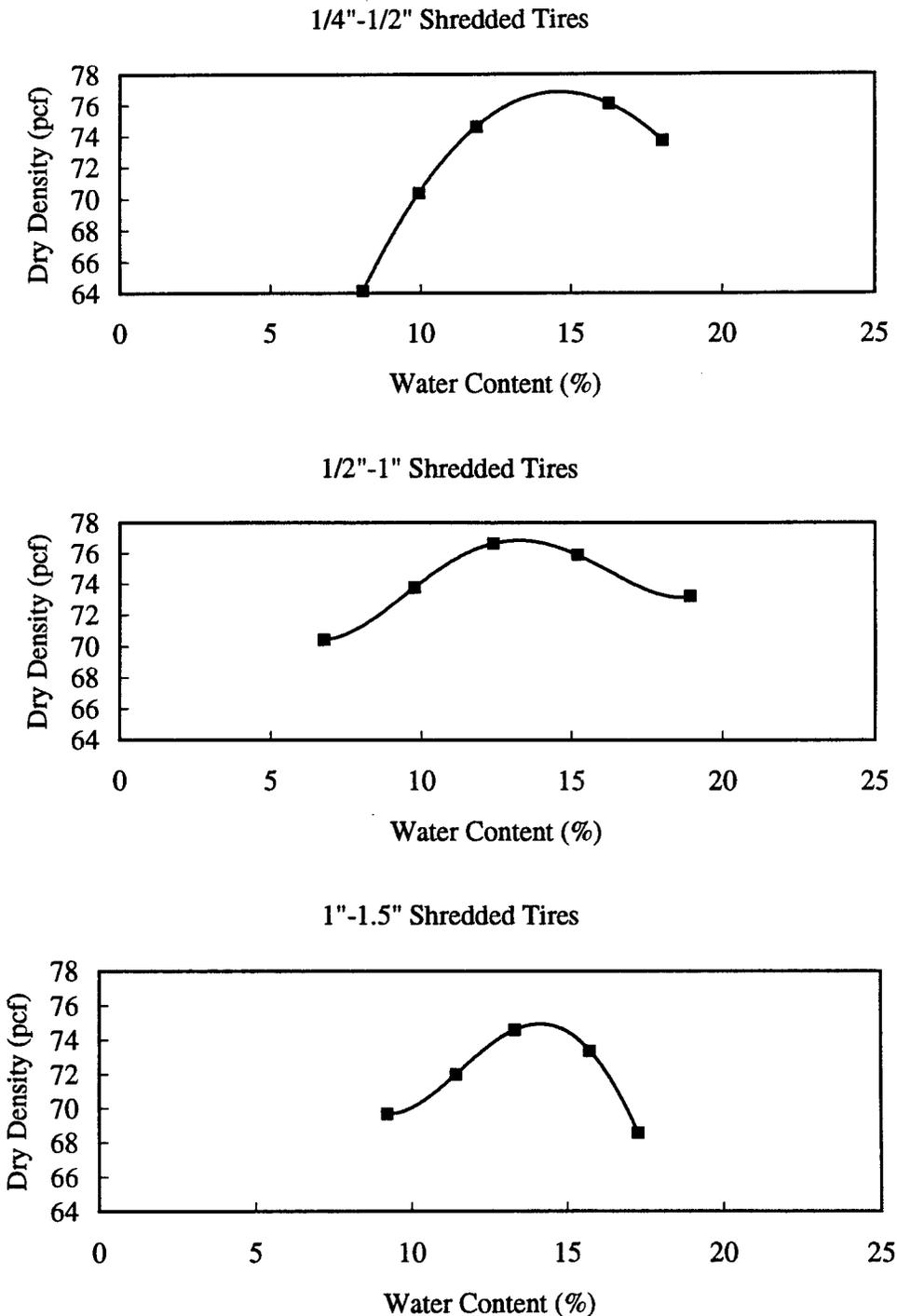


Figure A-7: Compaction curves for silt mixed with 50% shredded tire material.

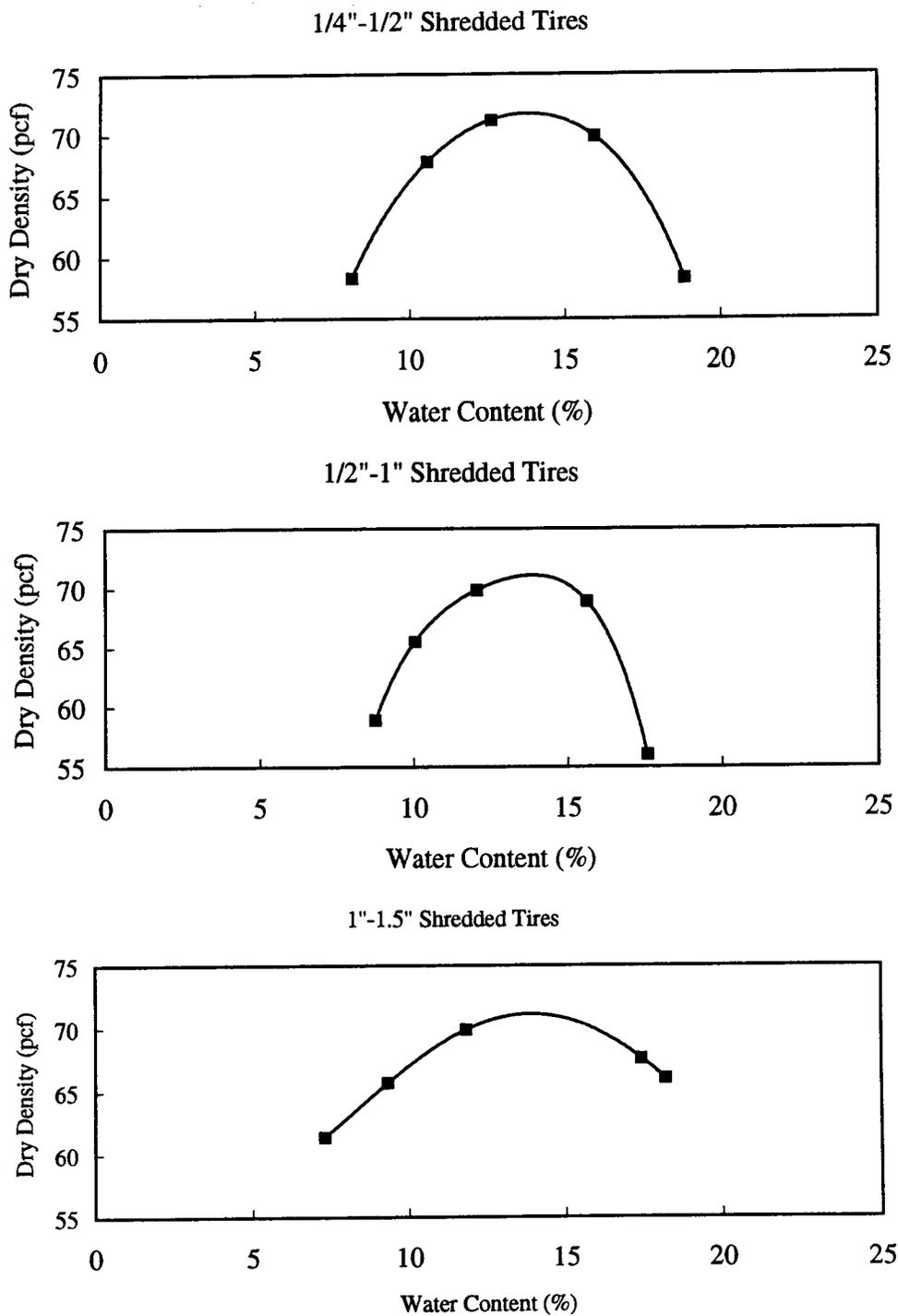


Figure A-8: Compaction curves for silt mixed with 60% shredded tire material.

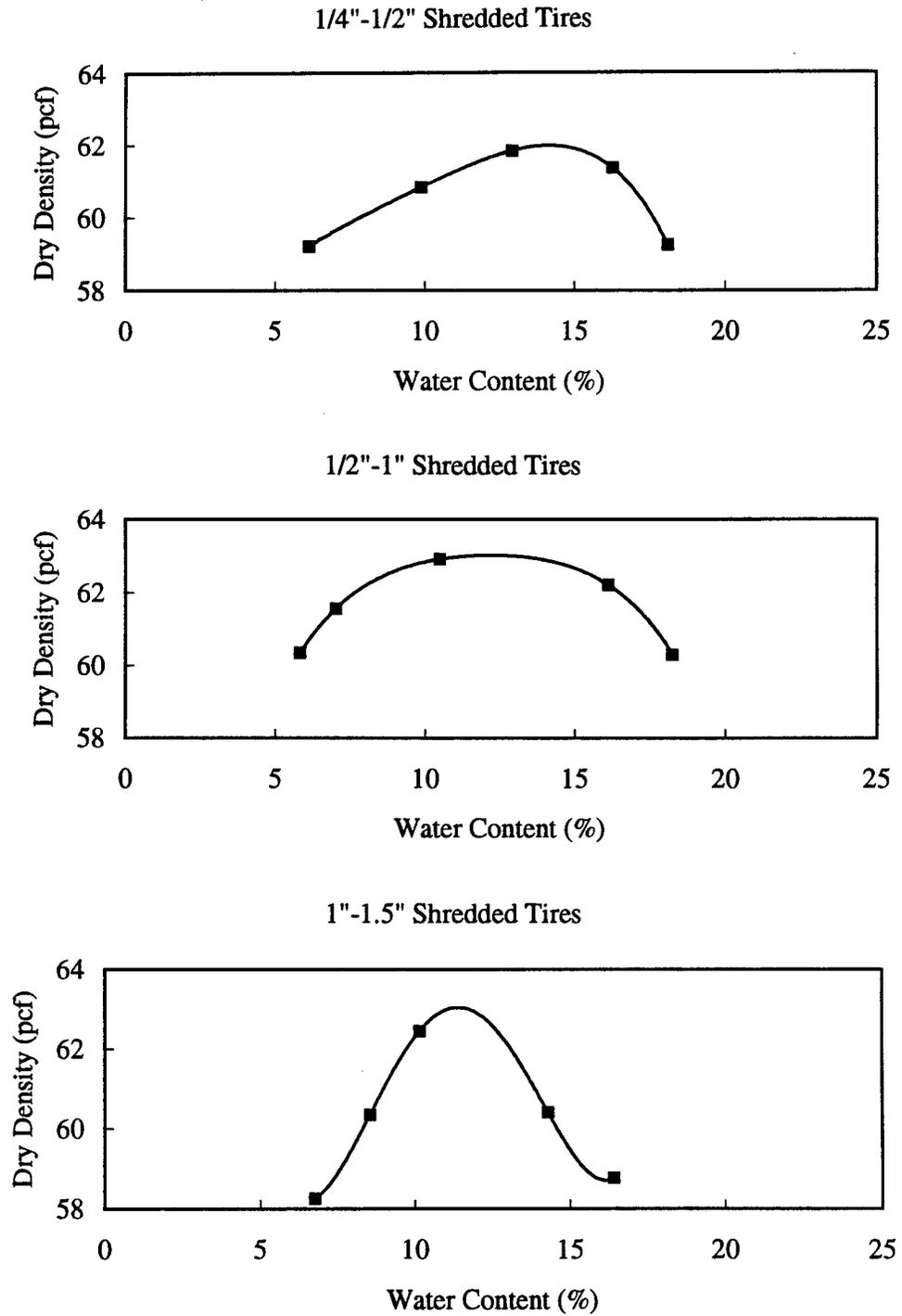


Figure A-9: Compaction curves for silt mixed with 70% shredded tire material.

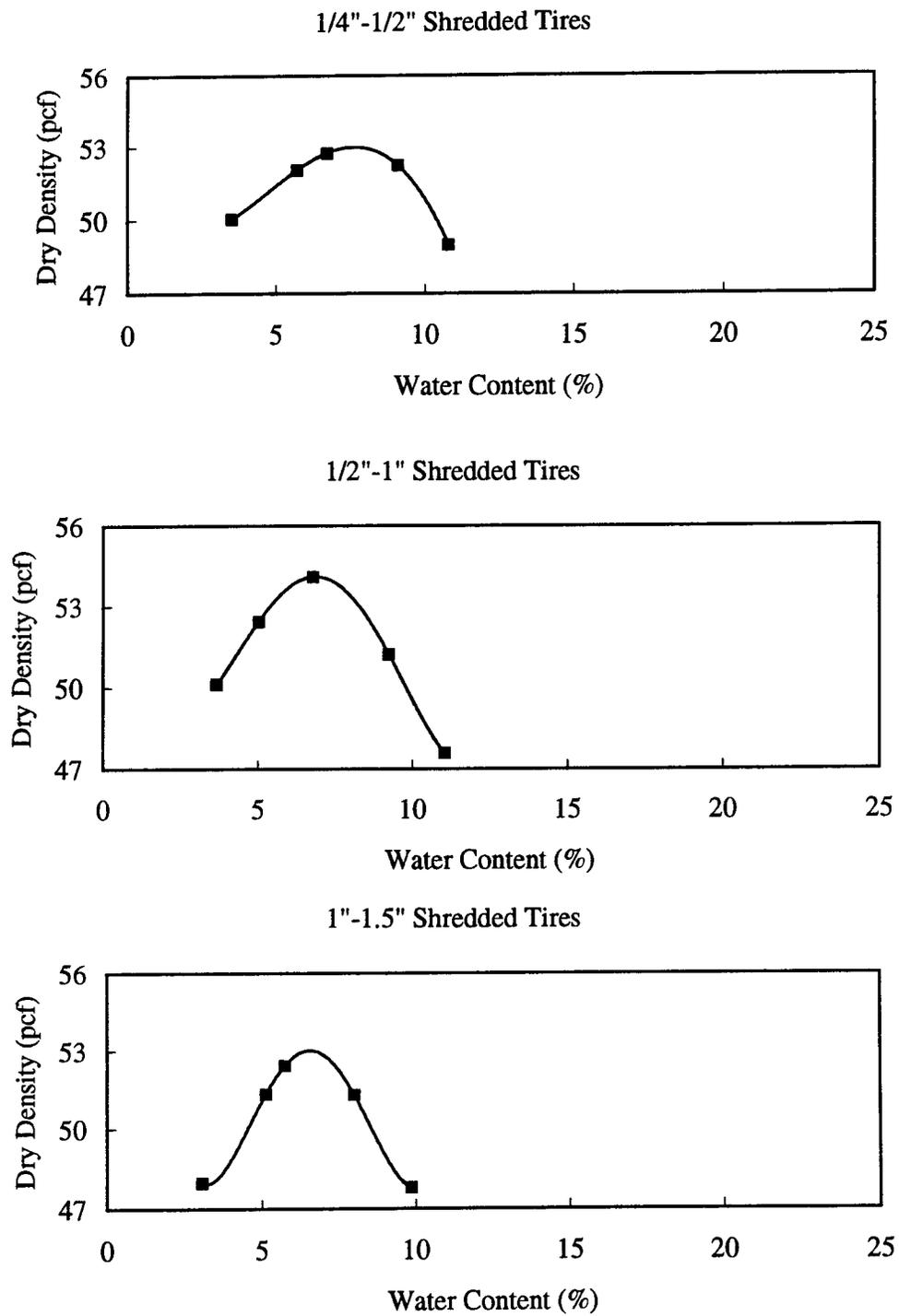


Figure A-10: Compaction curves for silt mixed with 80% shredded tire material.

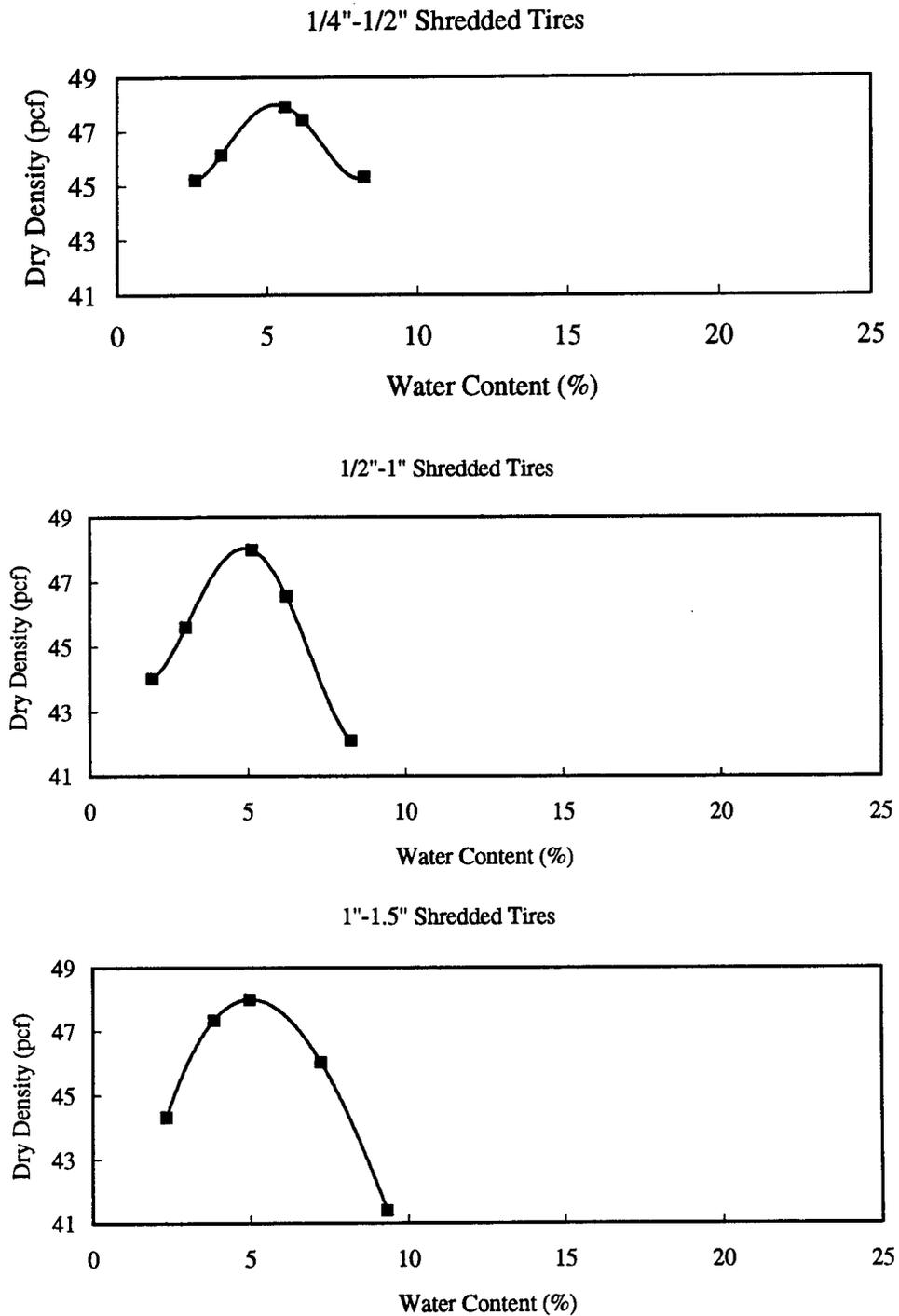


Figure A-11: Compaction curves for silt mixed with 90% shredded tire material.

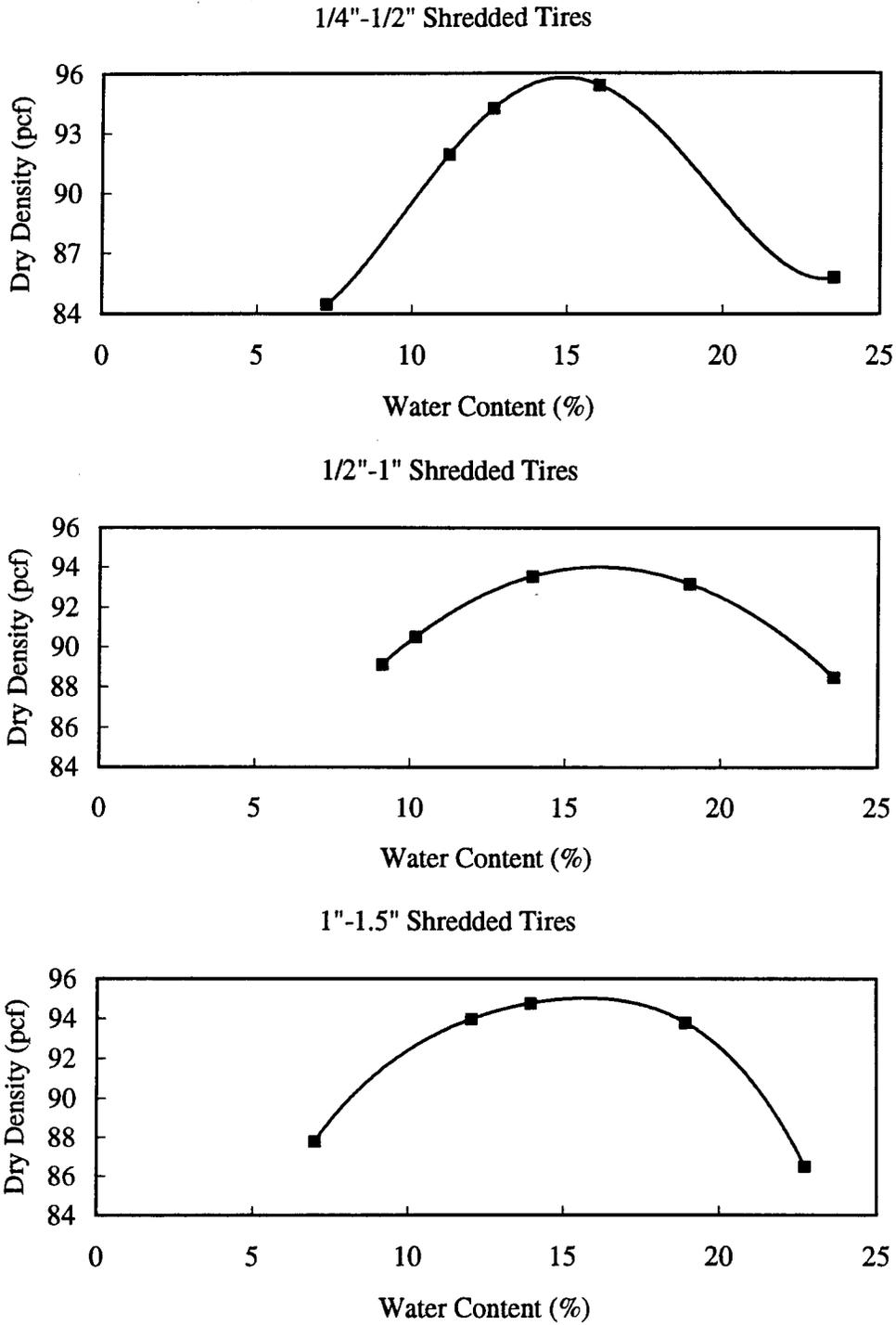


Figure A-12: Compaction curves for clay mixed with 10% shredded tire material.

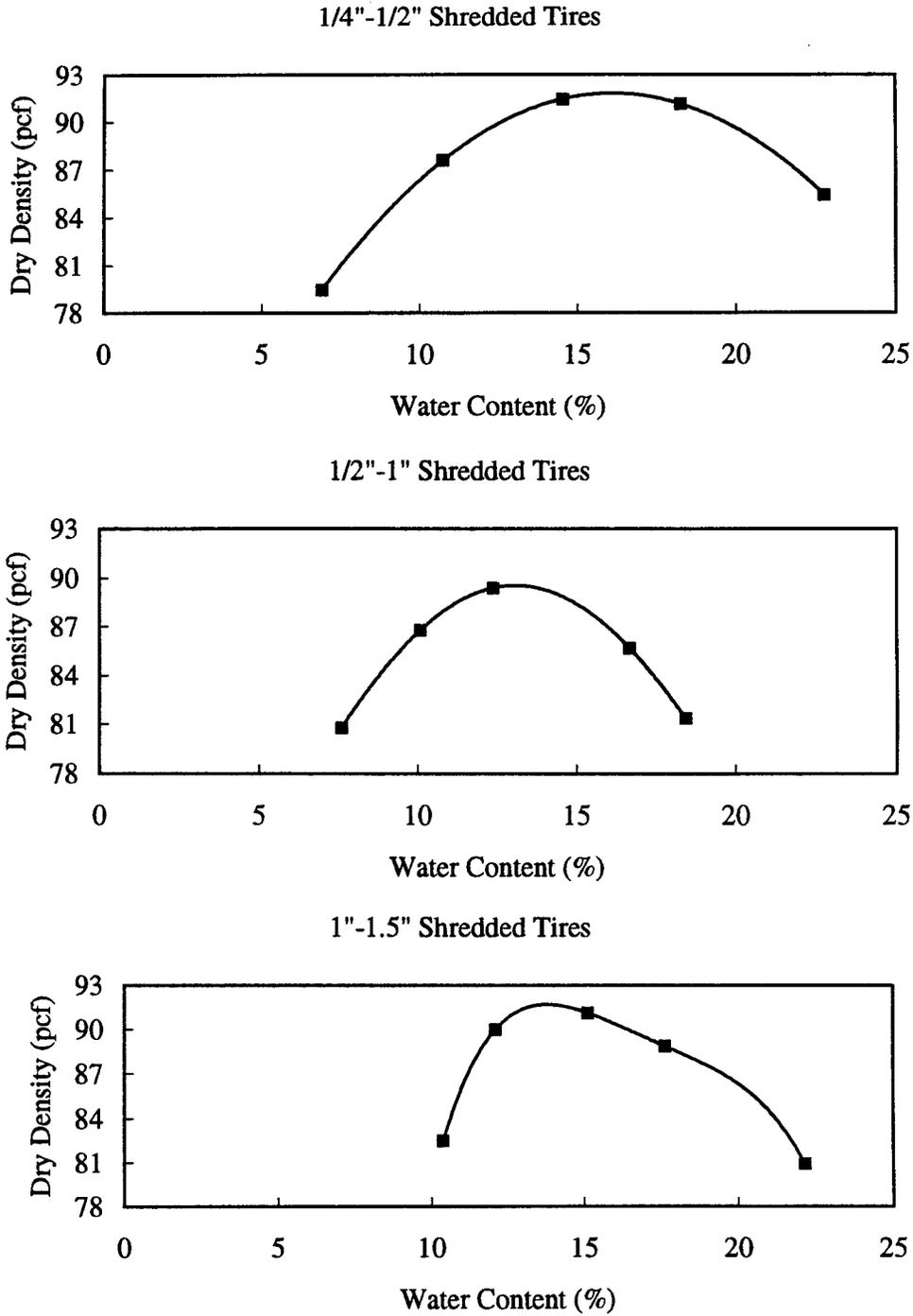


Figure A-13: Compaction curves for clay mixed with 20% shredded tire material.

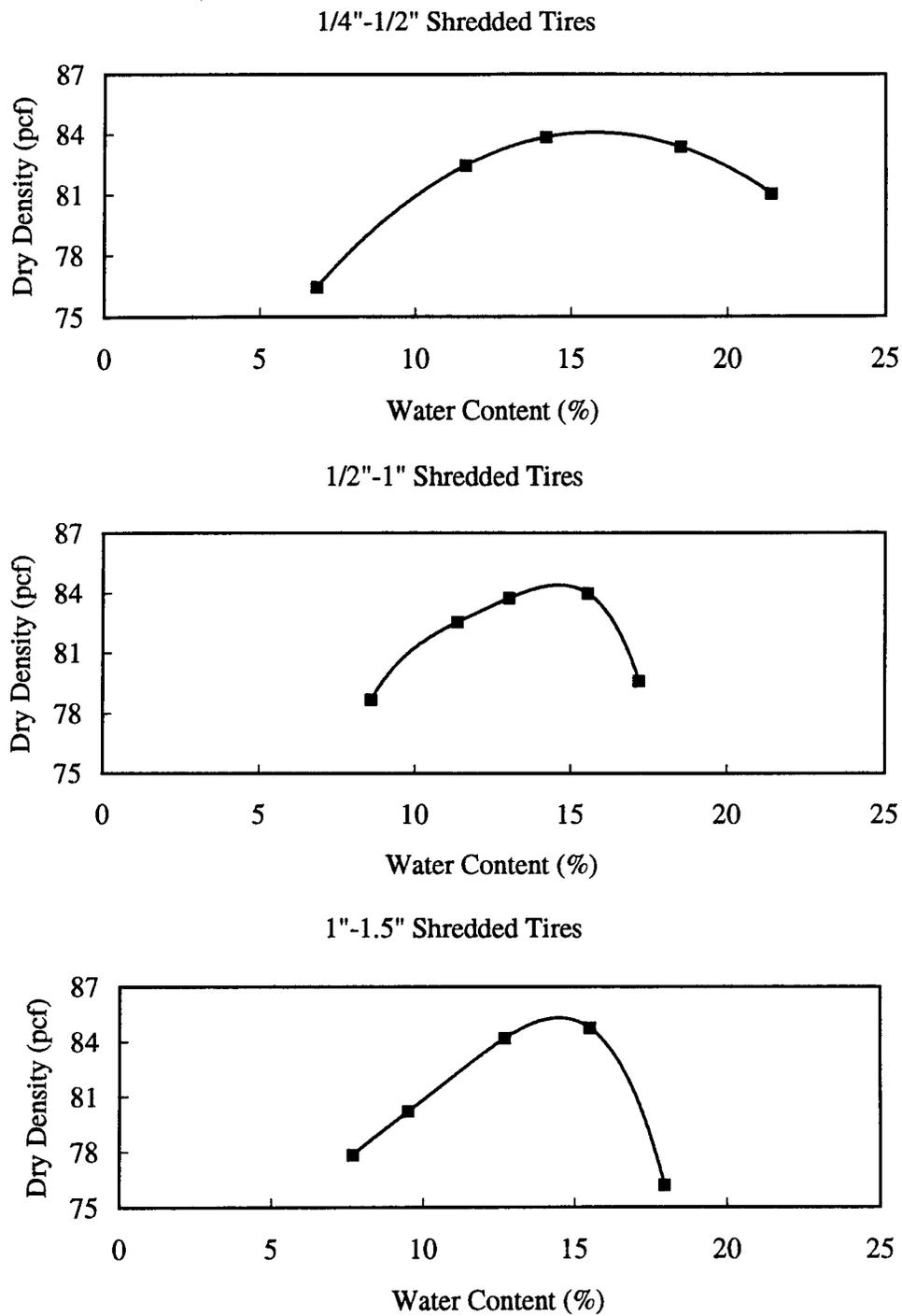


Figure A-14: Compaction curves for clay mixed with 30% shredded tire material.

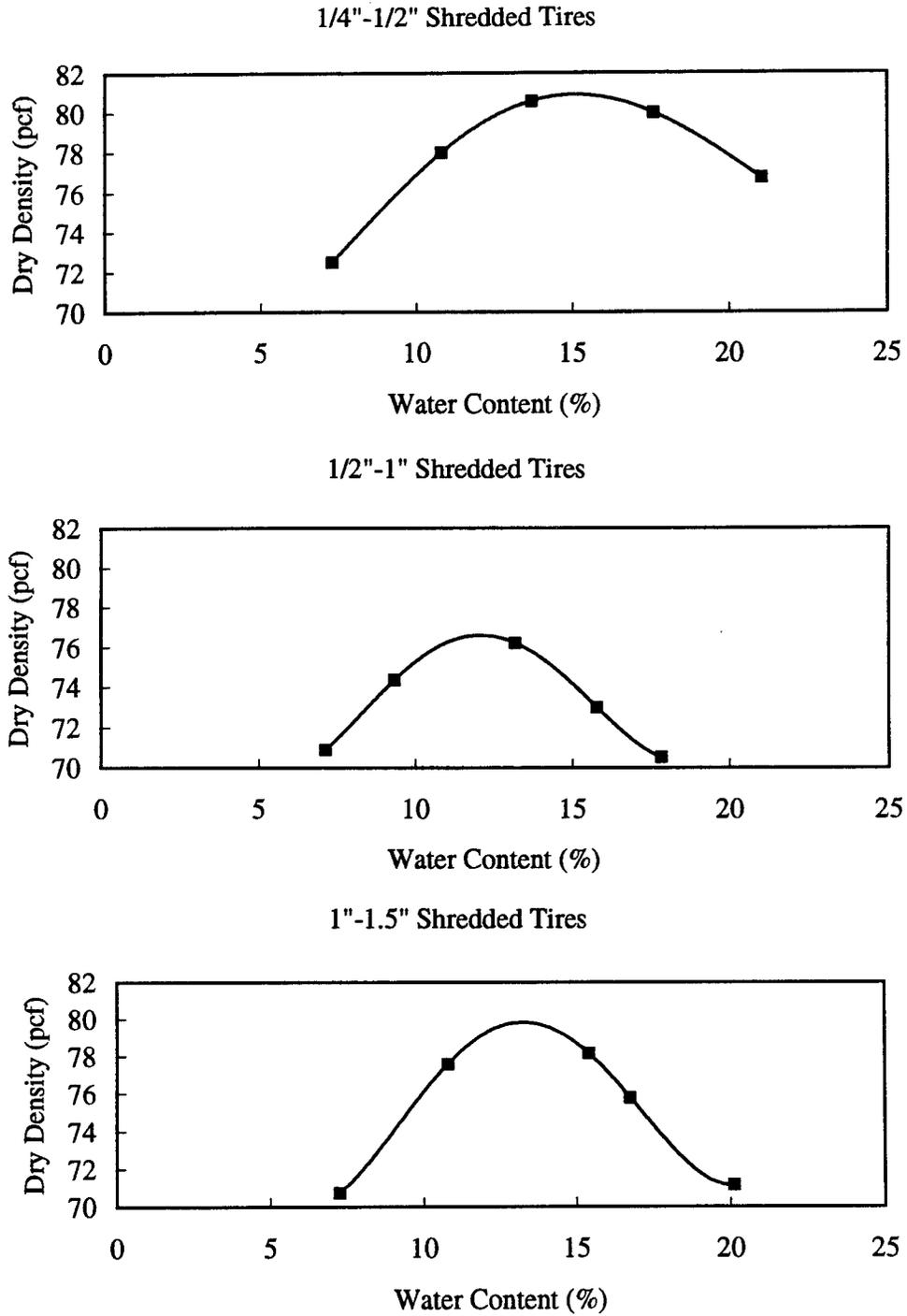


Figure A-15: Compaction curves for clay mixed with 40% shredded tire material.

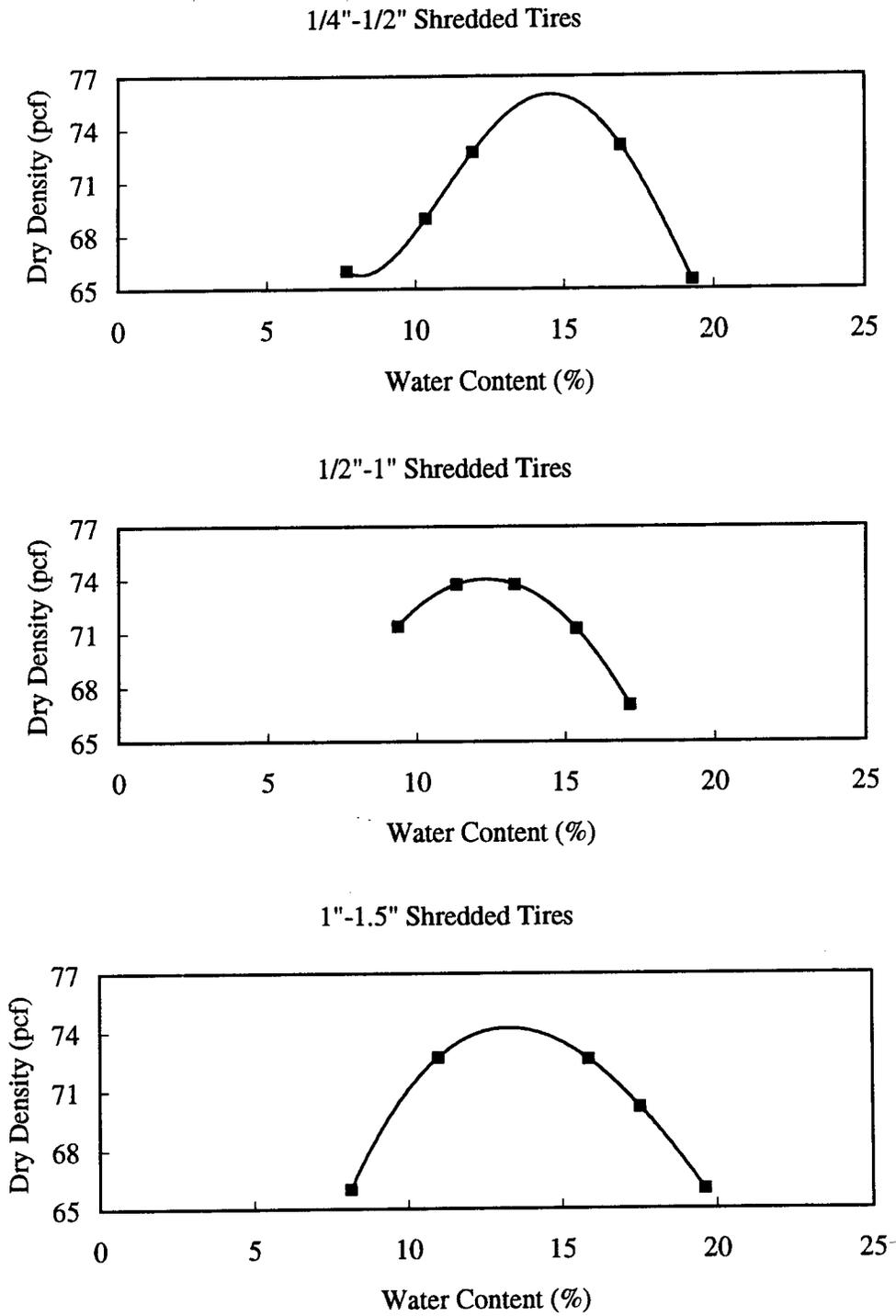


Figure A-16: Compaction curves for clay mixed with 50% shredded tire material.

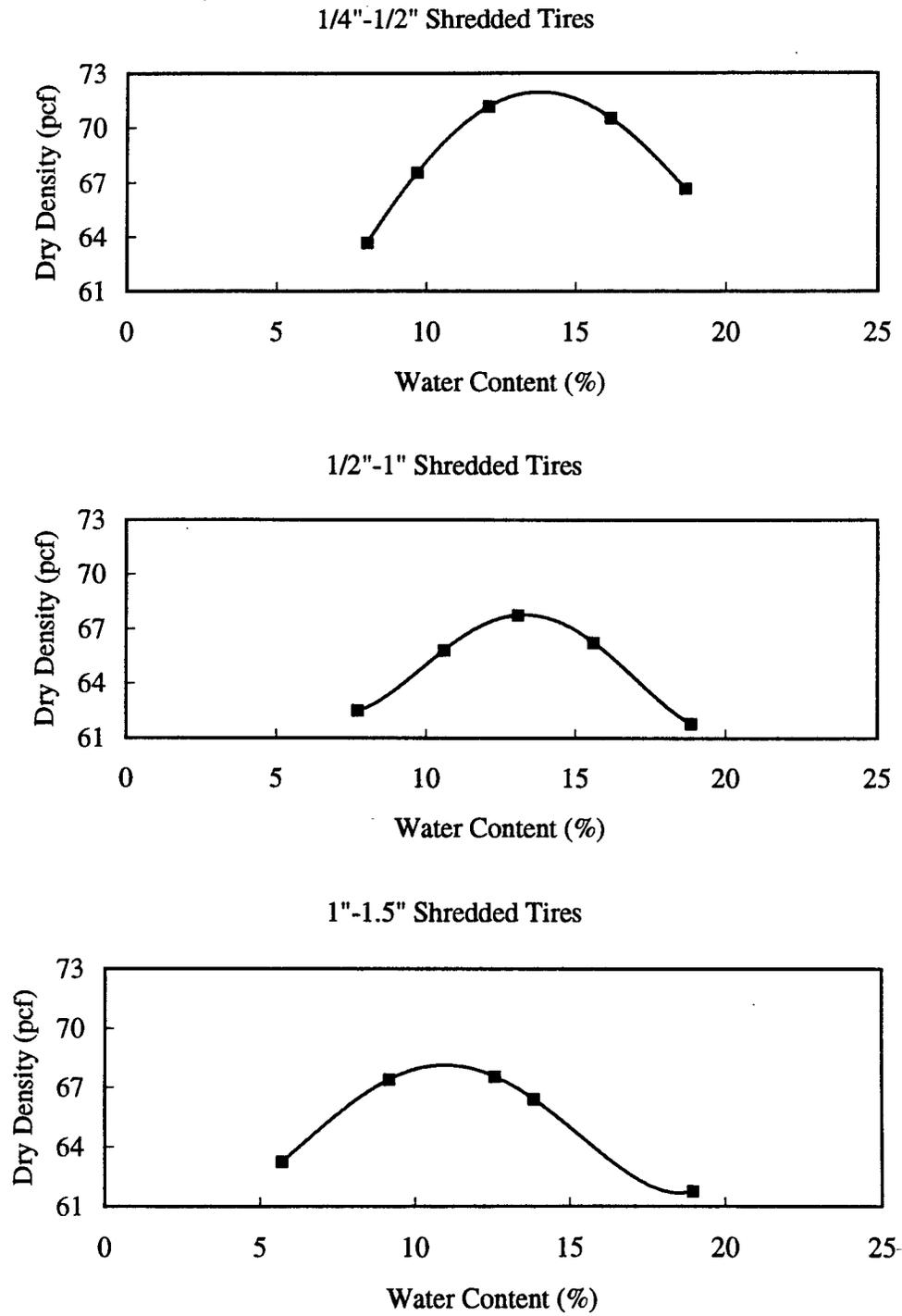


Figure A-17: Compaction curves for clay mixed with 60% shredded tire material.

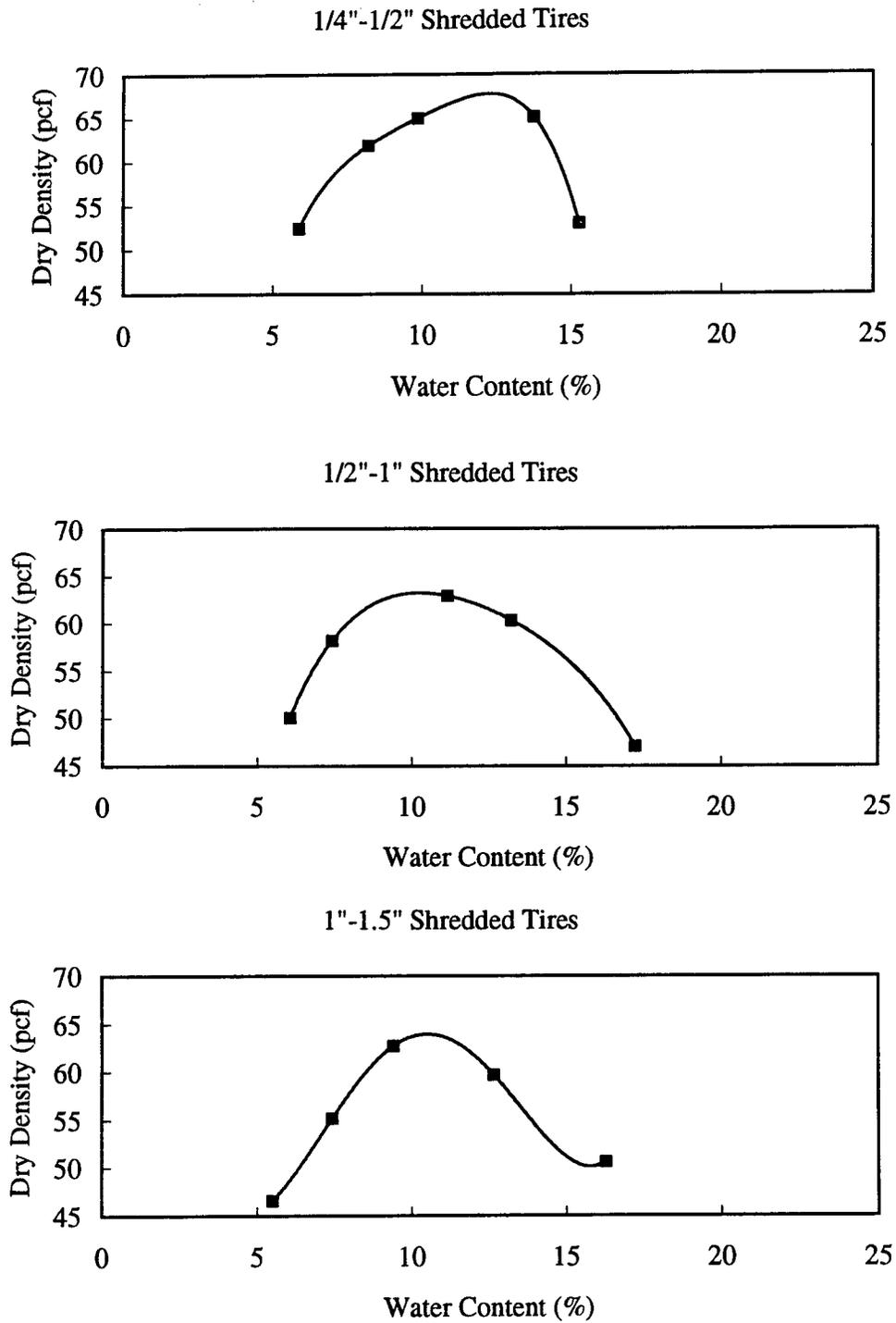


Figure A-18: Compaction curves for clay mixed with 70% shredded tire material.

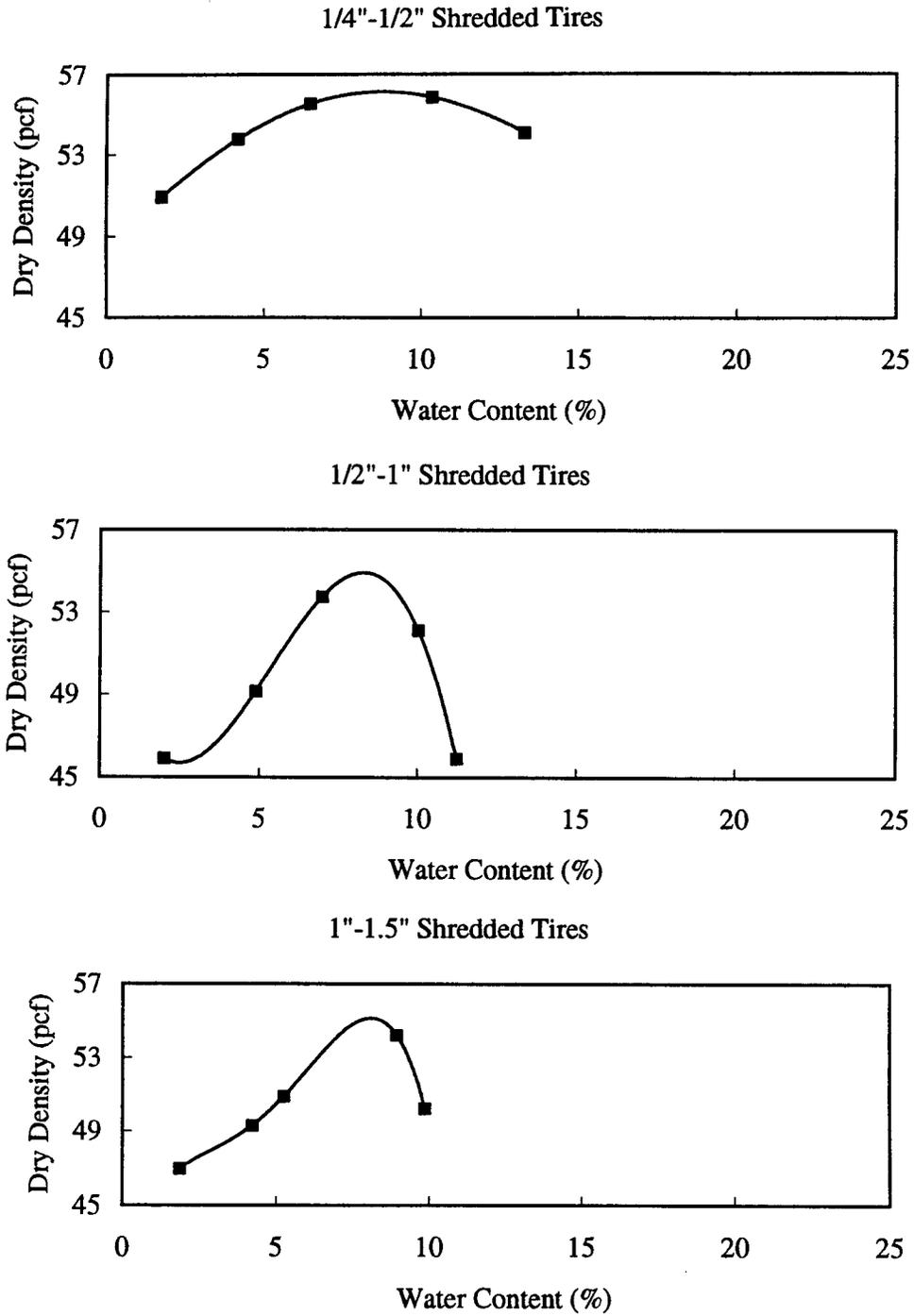


Figure A-19: Compaction curves for clay mixed with 80% shredded tire material.

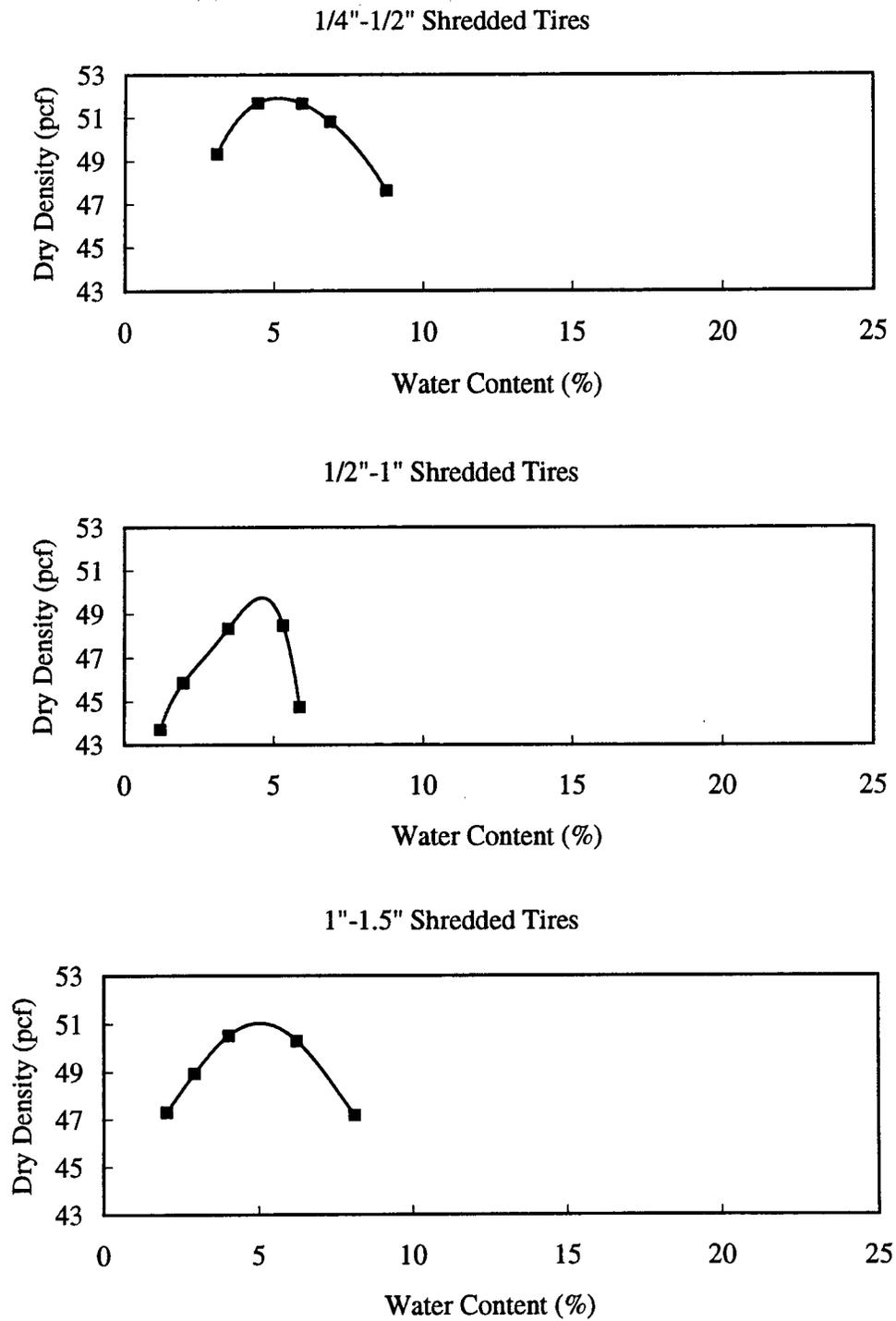


Figure A-20: Compaction curves for clay mixed with 90% shredded tire material.

APPENDIX B

RESULTS OF PERMEABILITY TESTS

Table B-1: Permeability for silt and silt-tire mixtures.

Shredded Tire Content (%)	Permeability (cm/sec)		
	Shredded Tire Size		
	1/4"-1/2"	1/2"-1"	1"-1.5"
0	4.48E-07	4.48E-07	4.48E-07
10	2.35E-06	4.96E-06	6.32E-06
20	4.19E-05	4.42E-05	5.46E-05
30	4.60E-04	5.02E-04	3.85E-03
40	1.03E-02	3.08E-02	5.60E-02
50	3.48E-02	7.55E-02	8.38E-02
60	8.37E-02	1.31E-01	1.49E-01
70	1.25E-01	1.46E-01	1.58E-01
80	1.32E-01	1.53E-01	1.60E-01
90	1.40E-01	1.62E-01	1.74E-01
100	1.64E-01	1.76E-01	1.80E-01

Table B-2: Permeability for clay and clay-tire mixtures.

Shredded Tire Content (%)	Permeability (cm/sec)		
	Shredded Tire Size		
	1/4"-1/2"	1/2"-1"	1"-1.5"
0	4.32E-08	4.32E-08	4.32E-08
10	3.43E-07	5.97E-07	6.64E-07
20	2.85E-06	6.38E-06	7.12E-06
30	8.17E-04	8.83E-03	1.25E-02
40	1.62E-02	3.77E-02	5.60E-02
50	3.48E-02	7.55E-02	8.38E-02
60	8.37E-02	1.24E-01	1.49E-01
70	1.00E-01	1.46E-01	1.58E-01
80	1.20E-01	1.53E-01	1.64E-01
90	1.40E-01	1.64E-01	1.73E-01
100	1.64E-01	1.76E-01	1.80E-01

APPENDIX C

RESULTS OF TRI-AXIAL TESTS

Table C-1: Friction angle, cohesion, and shear strength for silt and clay soils.

Soil Type	Friction Angle (degree)	Cohesion (psf)	Shear Strength (psf)
Silt	30	1656	2233
Clay	35	2635	3335

Table C-2: Friction angle, cohesion, and shear strength for silt-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Friction Angle (degree)	Cohesion (psf)	Shear Strength (psf)
1/4"-1/2"	10	32	1498	2122
	20	34	1122	1796
	30	36	985	1711
1/2"-1"	10	32	2808	3432
	20	34	2534	3208
	30	37	2362	3115
1"-1.5"	10	33	2837	3486
	20	35	2549	3249
	30	37	2434	3187

Table C-3: Friction angle, cohesion, and shear strength for clay-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Friction Angle (degree)	Cohesion (psf)	Shear Strength (psf)
1/4"-1/2"	10	36	1829	2555
	20	38	1289	2070
	30	32	1200	1824
1/2"-1"	10	37	2966	3692
	20	38	2765	3546
	30	32	2607	3230
1"-1.5"	10	37	3067	3820
	20	39	2895	3703
	30	31	2722	3322

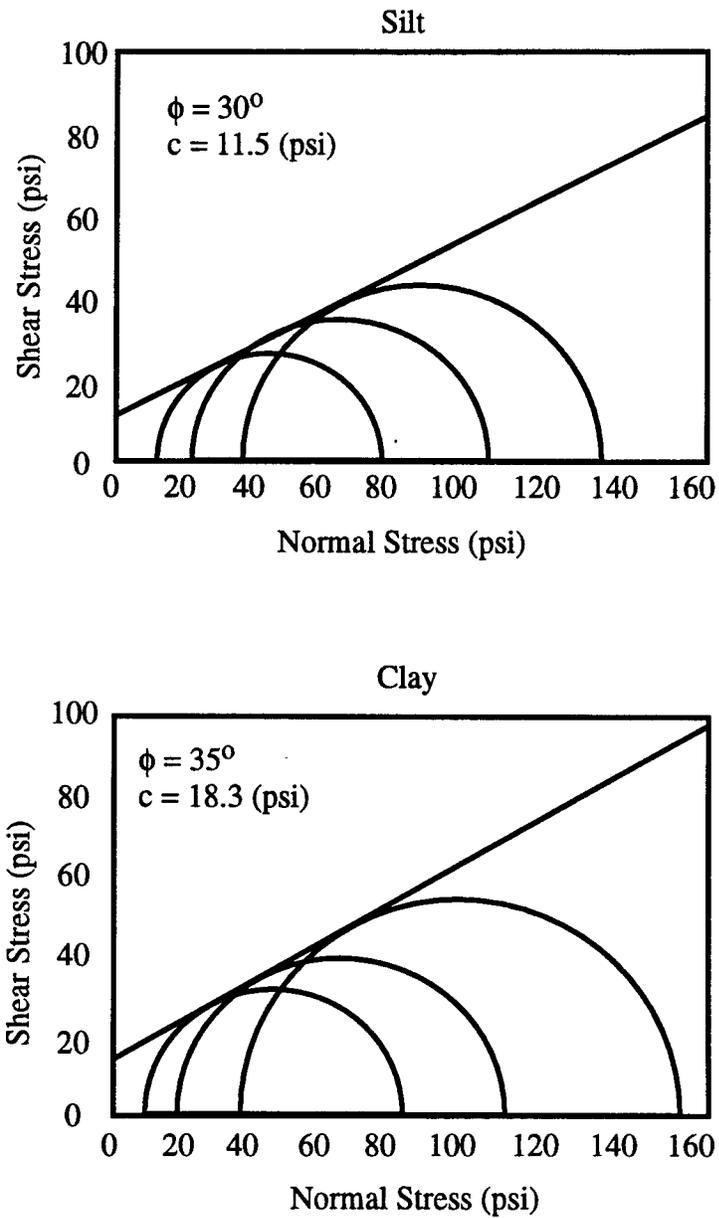


Figure C-1: Tri-axial test results for pure silt and clay soils.

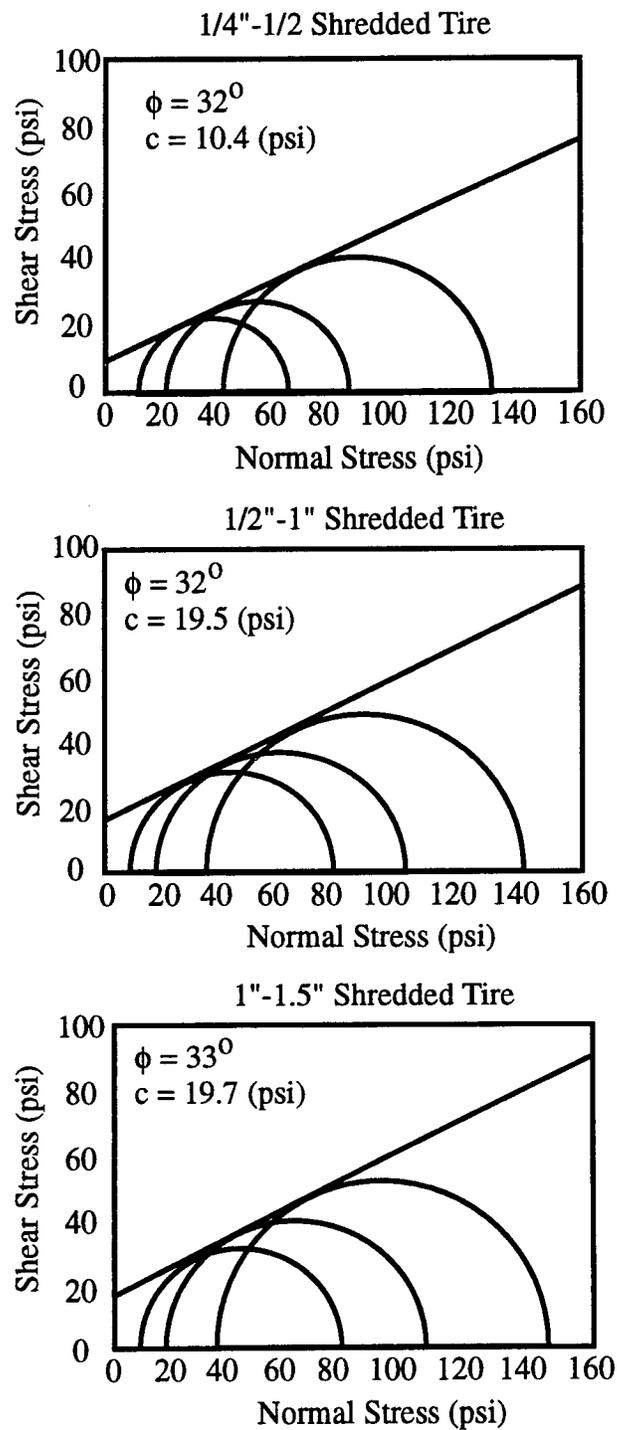


Figure C-2: Tri-axial test results for silt mixed with 10% shredded tire material.

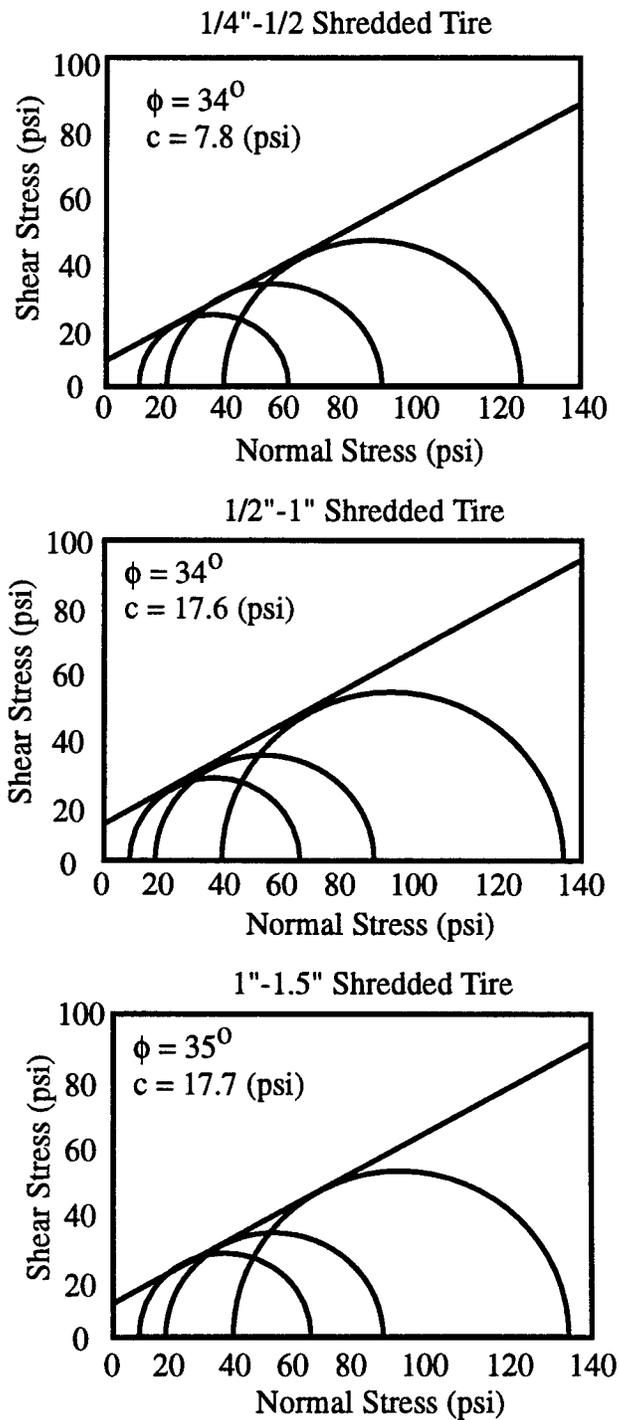


Figure C-3: Tri-axial test results for silt mixed with 20% shredded tire material.

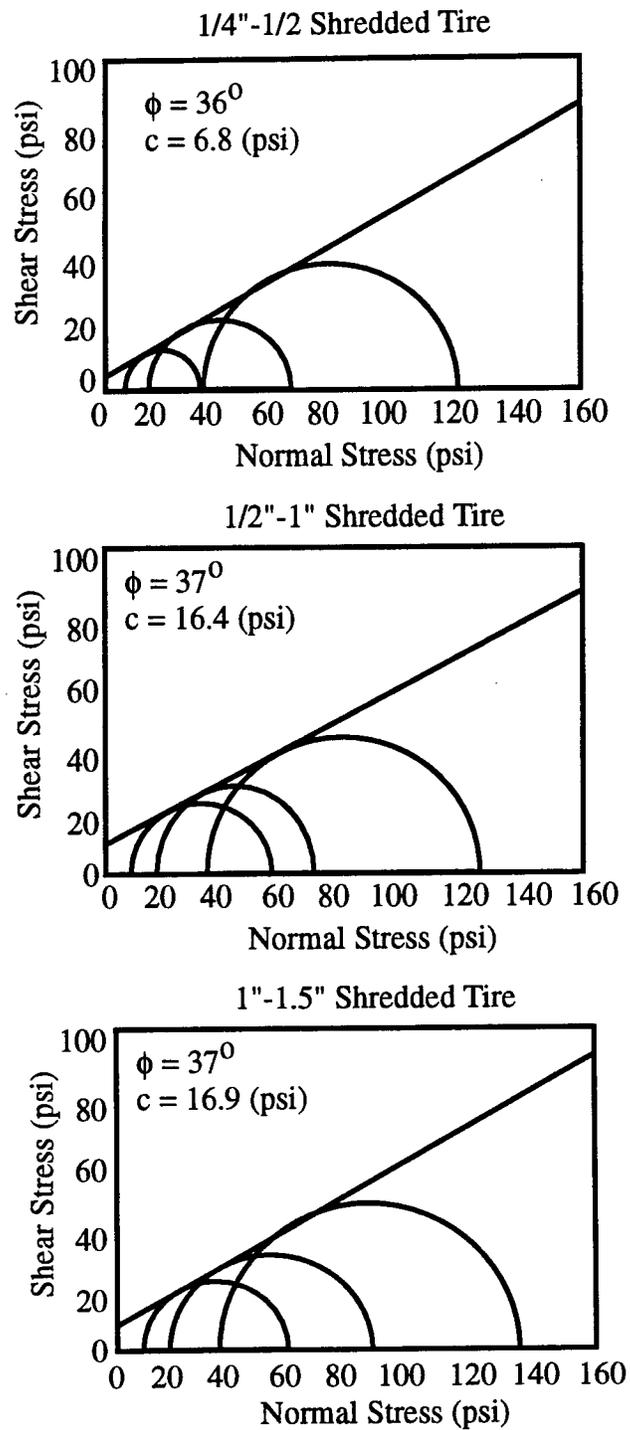


Figure C-4: Tri-axial test results for silt mixed with 30% shredded tire material.

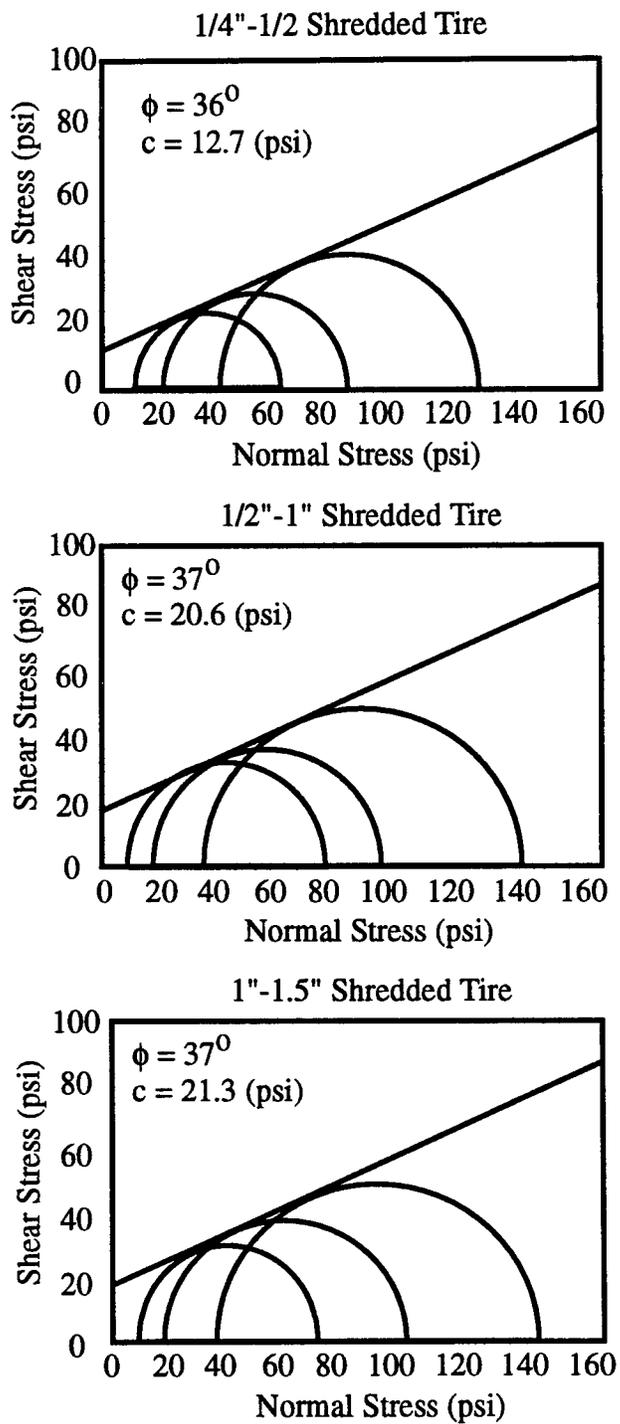


Figure C-5: Tri-axial test results for clay mixed with 10% shredded tire material.

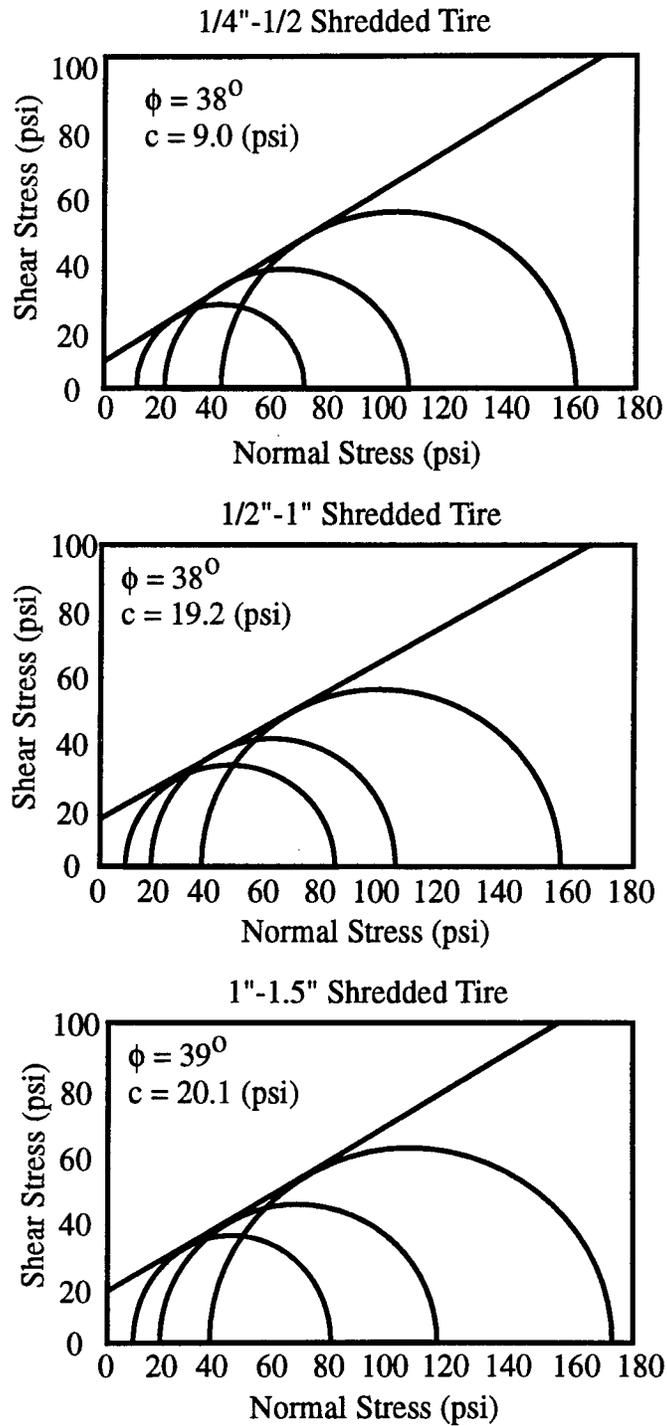


Figure C-6: Tri-axial test results for clay mixed with 20% shredded tire material.

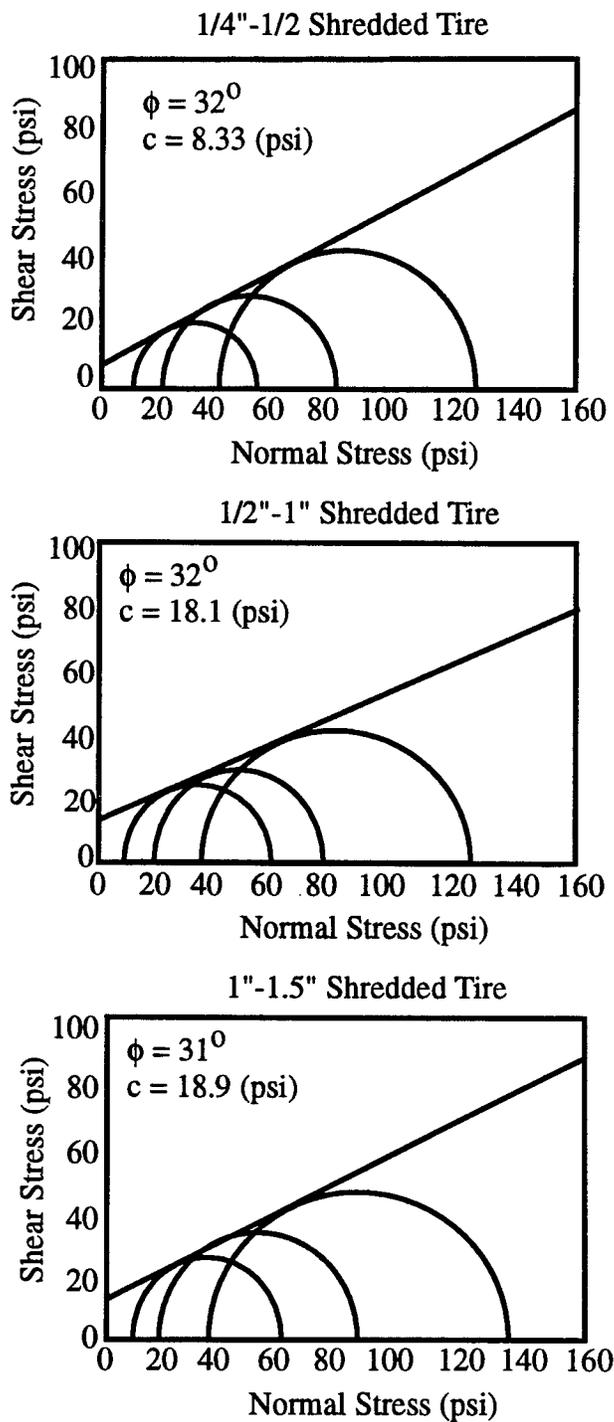


Figure C-7: Tri-axial test results for clay mixed with 30% shredded tire material.

APPENDIX D

RESULTS OF UNCONFINED COMPRESSION TESTS

Table D-1: Unconfined compressive strength for silt and silt-tire mixtures.

Shredded Tire Content (%)	Unconfined compressive strength (psf)		
	Shredded Tire Size		
	1/4"-1/2"	1/2"-1"	1"-3/2"
0	4077	4077	4077
10	3851	3398	2945
20	2942	2718	2492
30	2718	2149	1586
40	2265	1817	1359
50	1586	1133	0
60	1133	0	0
70	0	0	0
80	0	0	0
90	0	0	0
100	0	0	0

Table D-2: Unconfine compressive strength (psf) for clay and clay-tire mixtures.

Shredded Tire Content (%)	Unconfined compressive strength (psf)		
	Shredded Tire Size		
	1/4"-1/2"	1/2"-1"	1"-3/2"
0	6600	6600	6600
10	4809	4429	3851
20	3425	3273	2718
30	2833	2630	1910
40	2492	2243	1120
50	1919	1646	490
60	1469	1145	0
70	1133	906	0
80	901	686	0
90	679	0	0
100	0	0	0

APPENDIX E

RESULTS OF CONSOLIDATION TESTS

Table E-1: Compression index values for silt and clay.

Soil Type	Compression index	
	From consolidation test	From tri-axial test
Silt	0.050	0.033
Clay	0.100	0.035

Table E-2: Compression index values for silt-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Compression index from tri-axial test
1/4"-1/2"	10	0.046
	20	0.059
	30	0.066
1/2"-1"	10	0.047
	20	0.060
	30	0.072
1"-1.5"	10	0.049
	20	0.060
	30	0.073

Table E-3: Compression index values for clay-tire mixtures.

Shredded Tire Size	Shredded Tire Content (%)	Compression index from tri-axial test
1/4"-1/2"	10	0.038
	20	0.049
	30	0.077
1/2"-1"	10	0.040
	20	0.053
	30	0.078
1"-1.5"	10	0.040
	20	0.061
	30	0.085

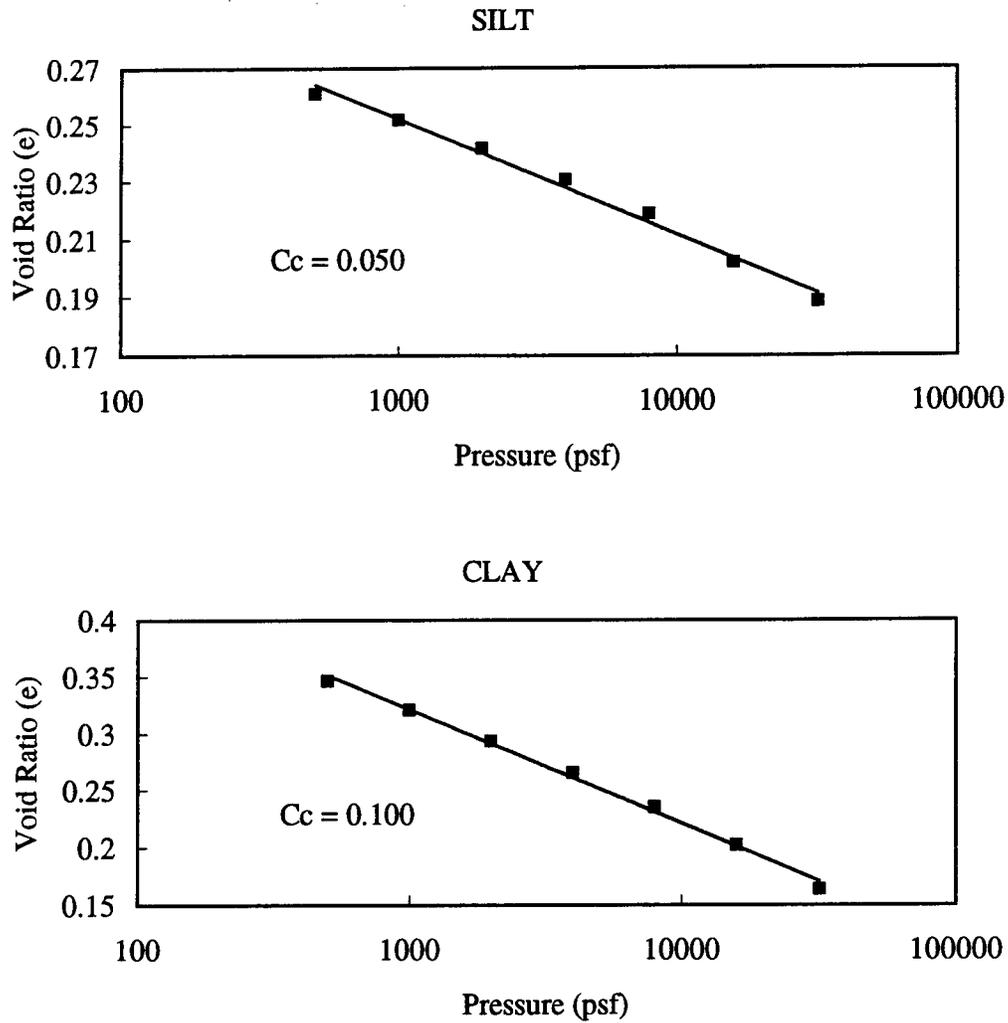


Figure E-1: Void ratio versus pressure for pure silt and clay as determined from consolidation test.

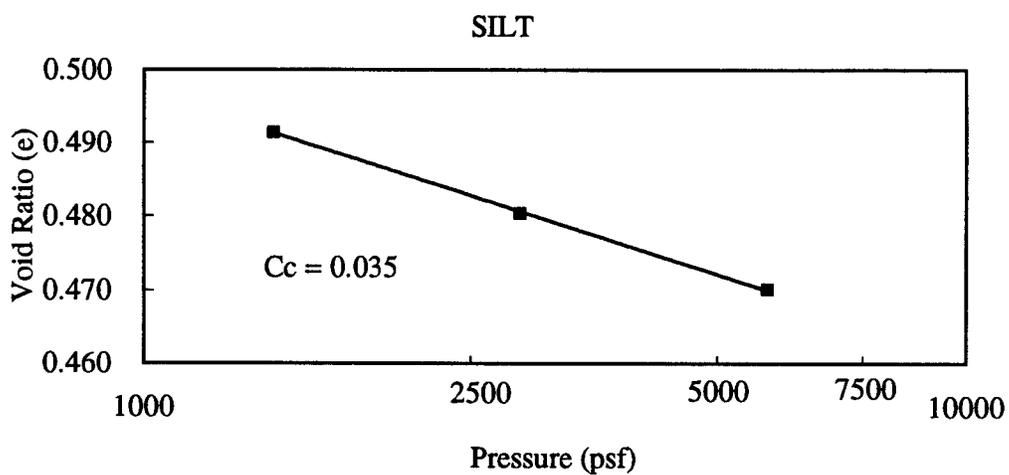
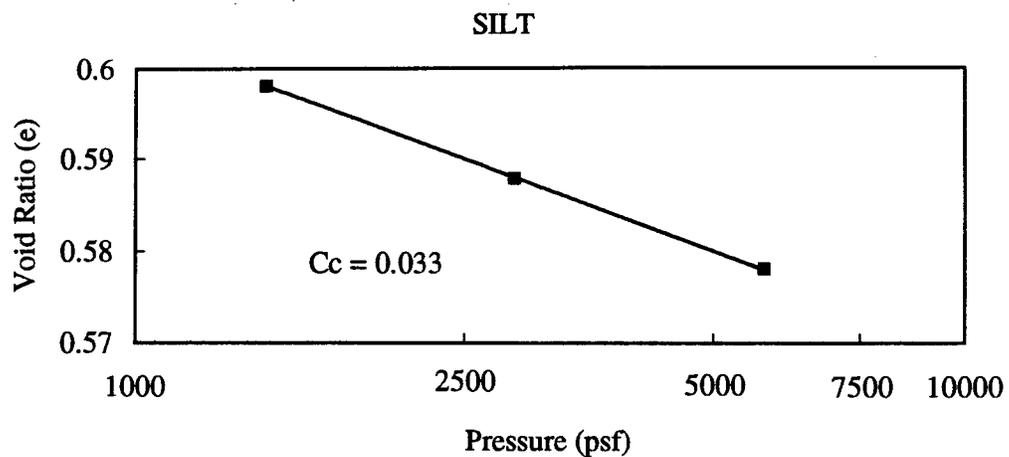


Figure E-2: Void ratio versus pressure for pure silt and clay as determined from triaxial test.

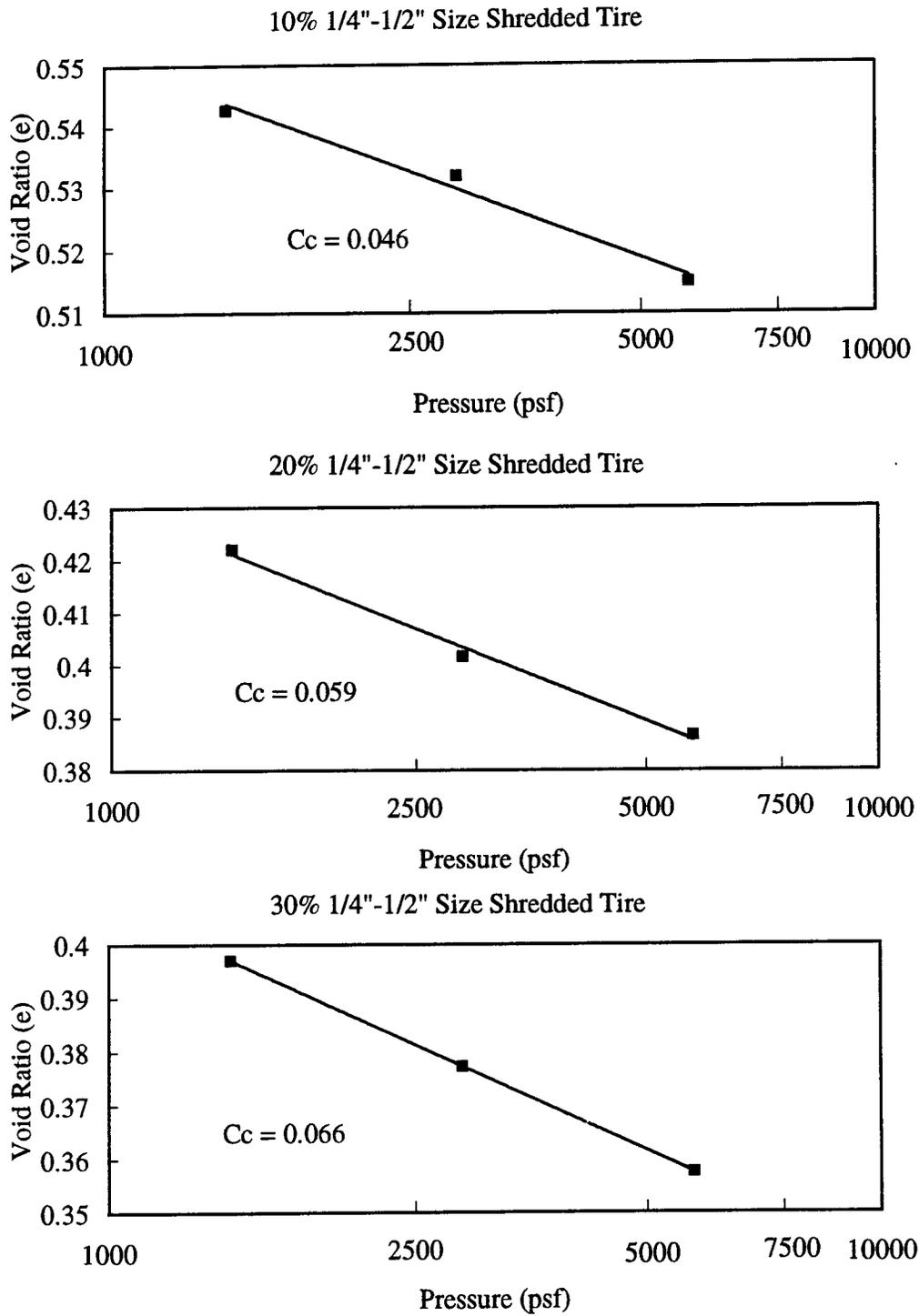


Figure E-3: Void ratio versus pressure for silt-tire mixtures as determined from triaxial test.

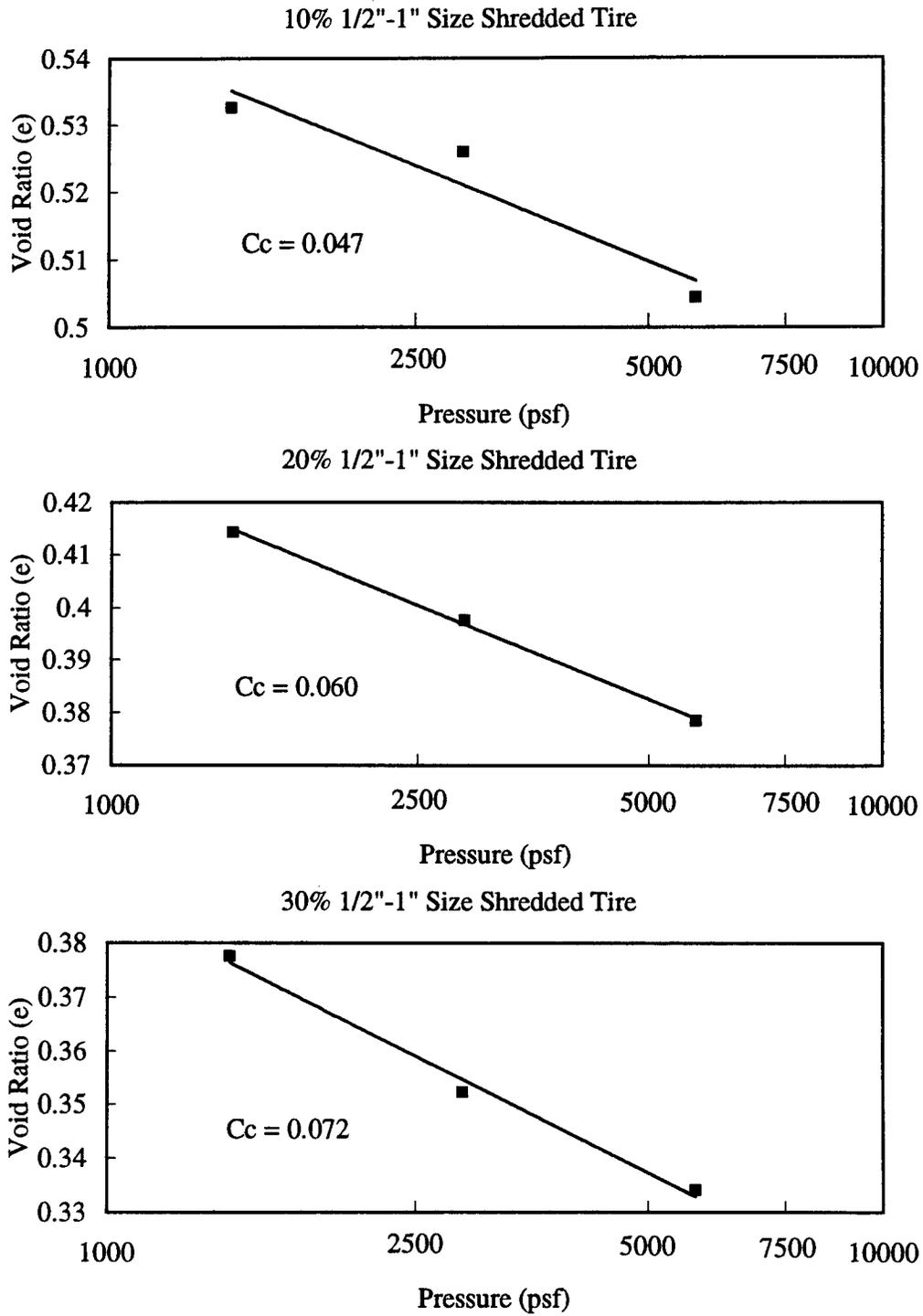


Figure E-4: Void ratio versus pressure for silt-tire mixtures as determined from triaxial test.

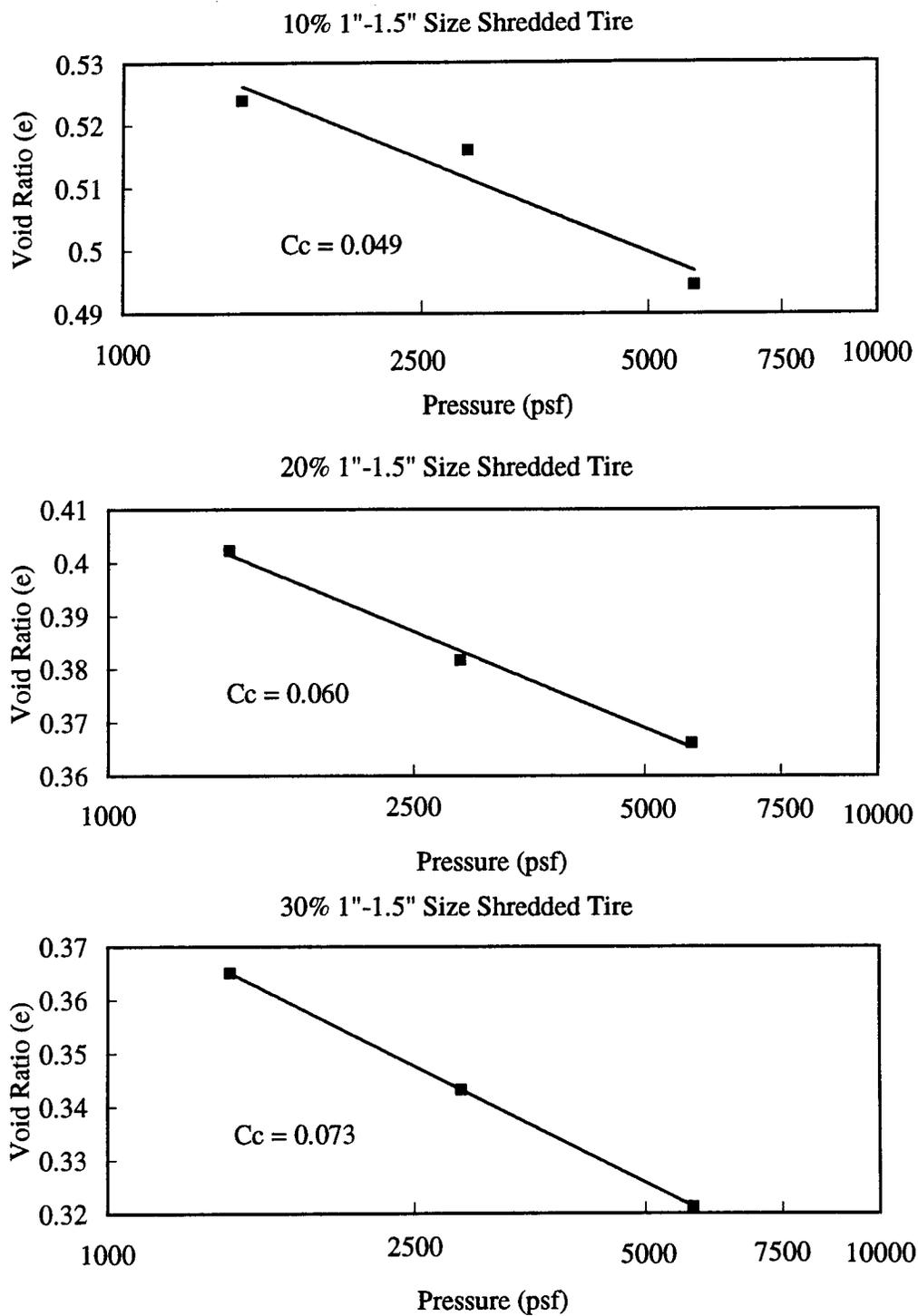


Figure E-5: Void ratio versus pressure for silt-tire mixtures as determined from triaxial test.

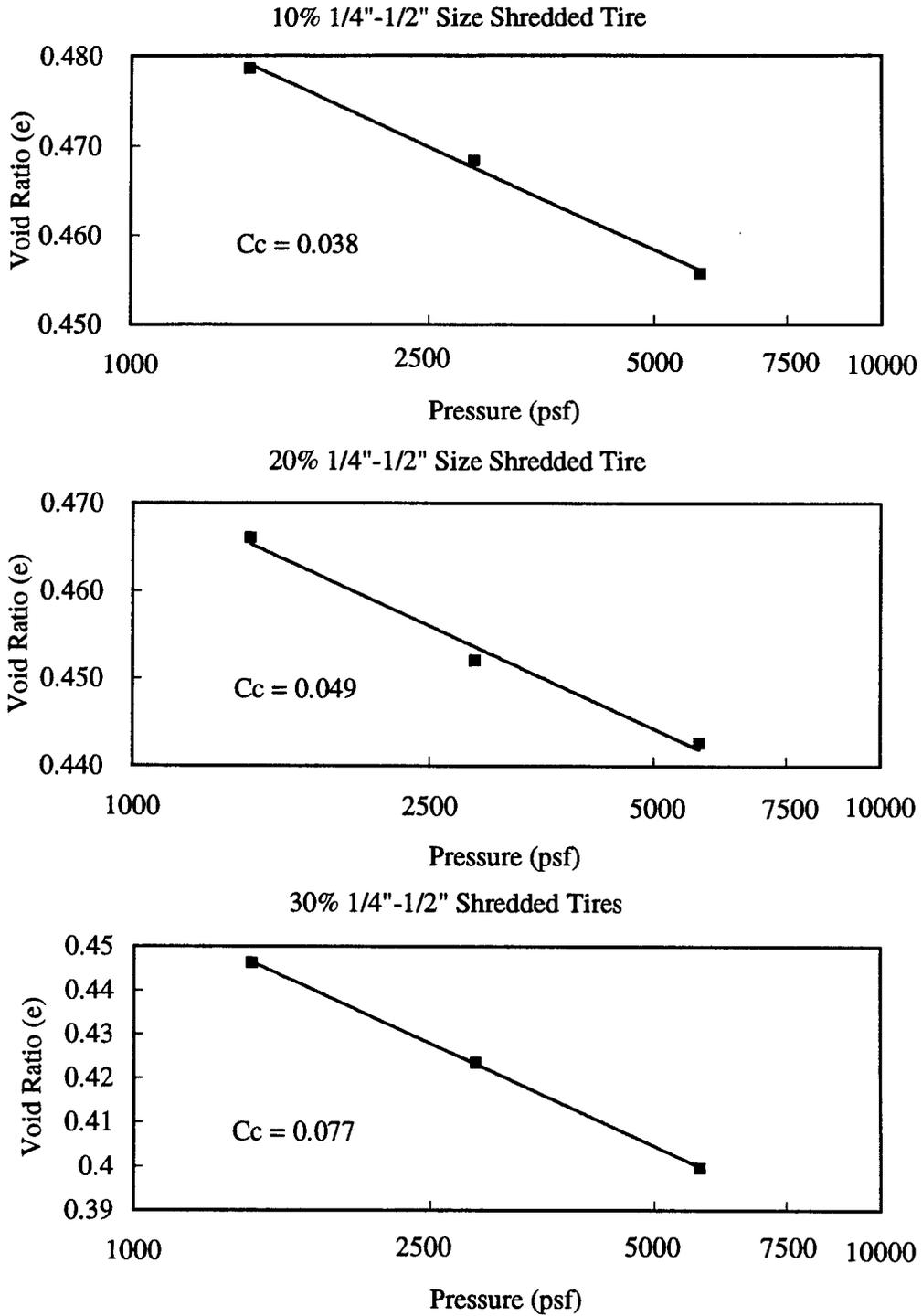


Figure E-6: Void ratio versus pressure for clay-tire mixtures as determined from triaxial test.

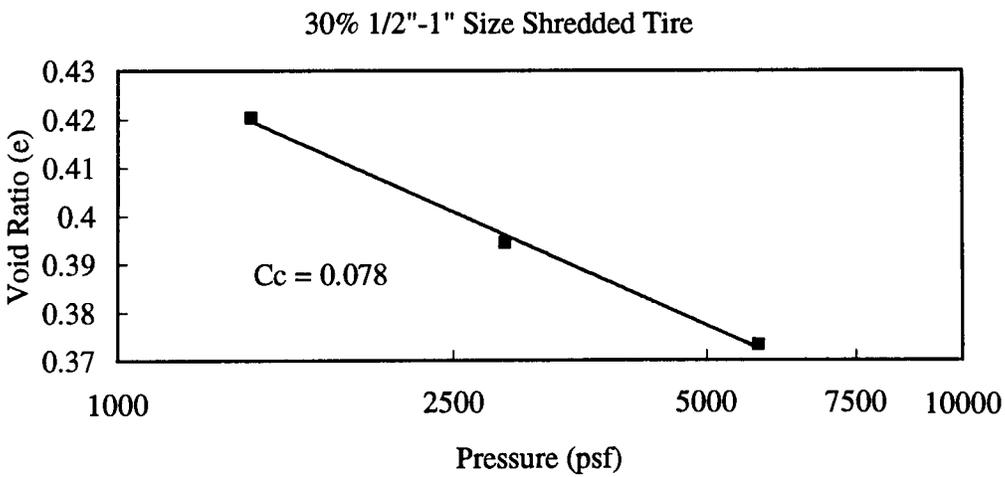
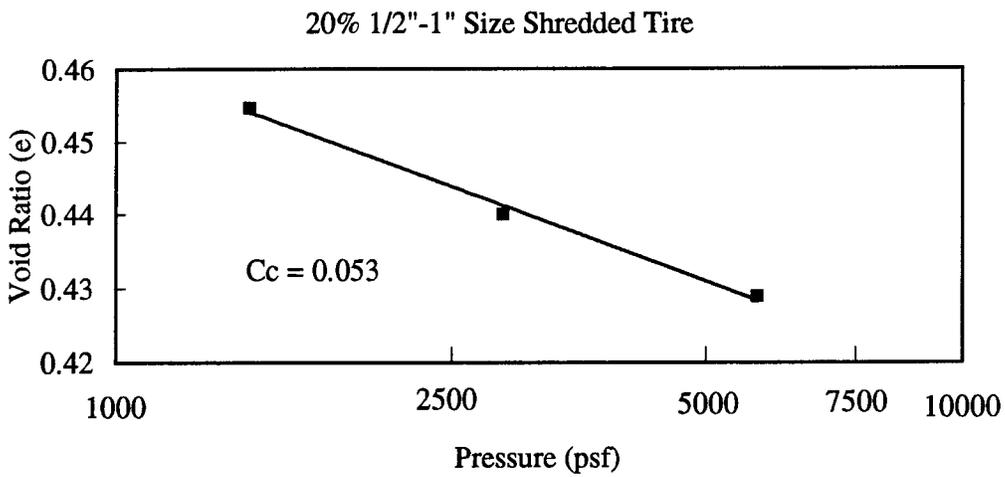
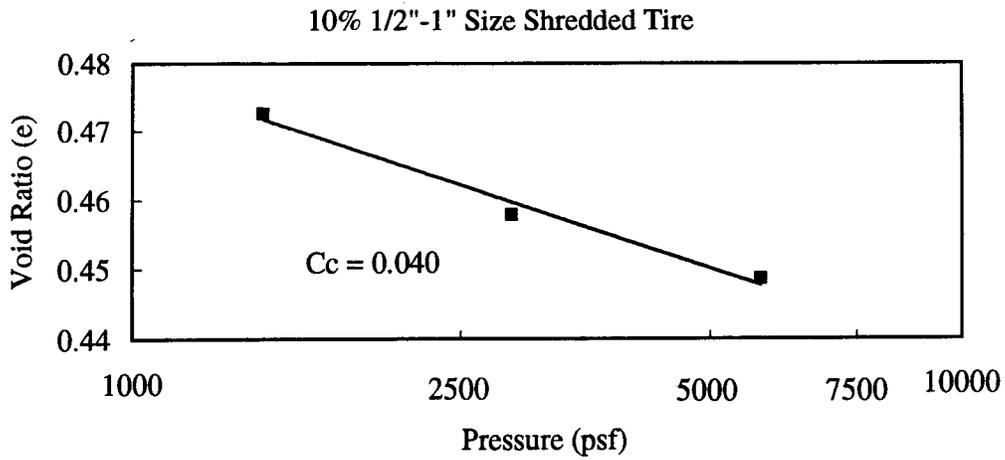


Figure E-7: Void ratio versus pressure for clay-tire mixtures as determined from triaxial test.

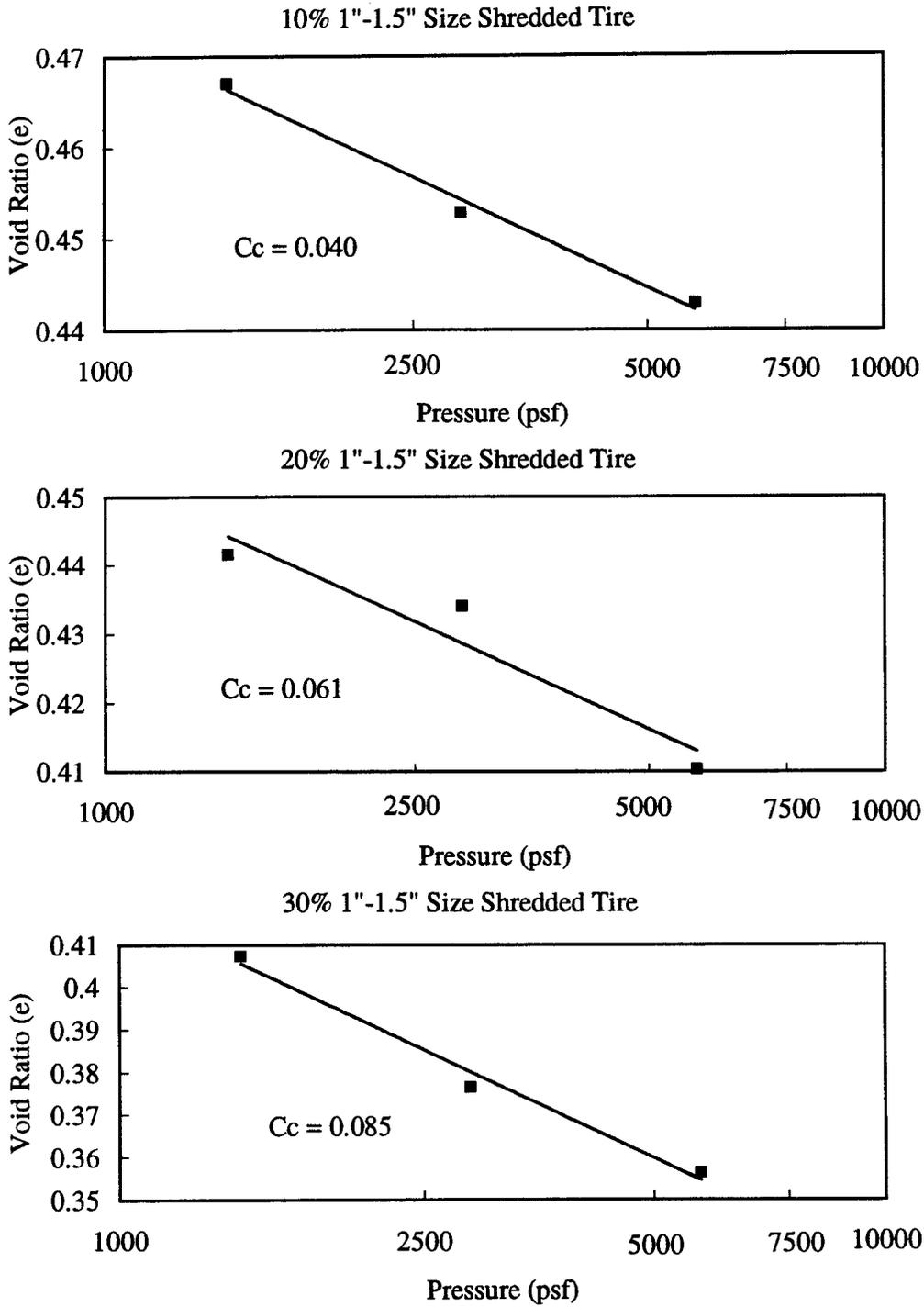


Figure E-8: Void ratio versus pressure for clay-tire mixtures as determined from triaxial test.

APPENDIX F

SETTLEMENT DATA FOR THE TEST EMBANKMENT

Table F-1: The height of the top of the embankment from the base of the embankment.

Survey Date	Height of the test embankment at different locations (mm)								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
5/30/96	54	54	54	54	54	54	54	54	54
9/18/96	51.51	50.16	46.97	52.33	51.33	49.50	52.15	50.75	49.13
9/25/96	51.25	49.78	46.40	52.11	51.06	49.04	51.89	50.56	48.80
10/2/96	50.73	49.29	45.91	51.96	50.92	48.89	51.57	50.40	48.28
10/16/96	50.25	49.00	45.60	51.54	50.51	48.70	51.05	50.24	47.98
11/1/96	50.21	48.86	45.55	51.30	50.47	48.62	51.03	50.22	47.90
11/16/96	50.16	48.83	45.46	51.28	50.29	48.51	50.82	50.04	47.76
12/7/96	50.11	48.80	45.37	51.26	50.19	48.38	50.61	49.82	47.62
1/30/97	49.87	48.48	44.61	51.05	50.10	48.17	50.24	49.75	47.43
2/24/97	49.69	48.21	44.52	50.66	49.95	47.74	49.78	49.34	47.10
3/22/97	49.57	48.13	44.50	50.64	49.77	47.64	49.54	49.03	47.05
5/6/97	49.40	47.79	44.48	50.63	49.61	47.56	49.43	48.81	46.91
6/4/97	49.38	47.74	44.41	50.59	49.59	47.50	49.42	48.77	46.86
6/30/97	49.36	47.74	44.41	50.58	49.58	47.50	49.41	48.76	46.85

APPENDIX G

SLOPE ANGLE DATA FOR THE TEST EMBANKMENT

Table G-1: The slope angle of the test embankment.

Survey Date	Slope Angle (degree)	
	East Side	West Side
5/30/96	35.6	33.78
9/18/96	32	35.2
9/25/96	34	34.6
10/2/96	33.8	32.8
10/16/96	36.1	33.12
11/1/96	34.5	34.6
11/16/96	33.8	34.3
12/7/96	34.1	34.5
1/30/97	34.6	34
2/24/97	33.8	34.2
3/22/97	34.2	33.9
5/6/97	36	35.2

APPENDIX H

RESULTS OF LOI TESTS

Table H-1: Results of loss on ignition (LOI) test.

Loss on ignition (LOI)		
Tire Size		
1/4"-1/2"	1/2"-1"	1"-1.5"
65.94	75.6	66.88
65.83	71.35	62.36
73.45	69.71	57.68
69.76	63.49	71.91
73.53	87.18	62.47
66.1	77.49	83.59
71.43	72.13	83.75
67.77	69.66	67.86
70.19	71.54	75.67
75.47	74.14	62.61
71	72.06	66.85
69.57	71.68	79.4
73.17	71	78.76
70.26	70.03	66.08
69.06	68.87	75.24
68.47	73.39	77.26
69.34	69.21	63.43
70.25	71.64	69.15
71.09	63.72	76.03
68.91	70.92	70.31

APPENDIX I

RESULTS OF BULK CHEMICAL ANALYSIS

Table I-1: Detection limit* of equipment** used for bulk analysis.

(a) data provided by manufacturer (Instrumentation Laboratory, 1982; Perkin-Elmer, 1985)

Leachate Concentration (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.023	0.0013	0.00019	0.000003	0.00002	0.00001	0.00002	0.0046	0.0014	0.00005	0.0018

(b) determined by blank sample

Leachate Concentration (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.2	0.33	0.21	0.0006	0.0006	0.0003	0.0001	0.2	0.3	0.0003	0.45

* The detection limit was three times of the standard deviation of concentration of blank sample.

** The elements of aluminum, barium, calcium, manganese, iron, and zinc were analyzed in ICP and the elements of cadmium, chromium, cobalt, copper, and lead were analyzed in GFAA.

Table I-2: Results of bulk analyses for 1/4"-1/2" size tire chips.

ion	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
Normal- ized Concen- tration (ppm)	0.73	4.62	2.25	0.01	0.70	0.12	0.03	460	3.23	0.49	1167
	1.95	3.36	1.86	0.01	0.58	0.16	0.04	675	1.47	0.39	2471
	0.84	3.15	2.05	0.01	0.65	0.13	0.02	654	1.87	0.13	2704
	0.94	2.86	1.86	0.02	0.57	0.23	0.04	615	2.25	0.23	2432
	1.94	2.68	1.86	0.02	1.54	0.07	0.02	364	1.42	0.17	2392
	0.96	3.44	3.43	0.01	1.51	0.19	0.05	428	2.15	0.17	1932
	2.04	2.90	1.95	0.02	3.51	0.23	0.03	233	1.20	0.17	2526
	0.55	2.54	1.85	0.02	0.93	0.57	0.05	269	1.86	0.18	2942
	0.94	2.93	2.05	0.03	0.63	0.07	0.05	299	1.32	0.19	2598
	1.65	2.08	1.46	0.03	0.49	0.26	0.03	363	1.32	0.49	1981
	1.26	4.00	1.75	0.02	1.27	0.12	0.02	368	2.11	0.19	1708
	0.32	5.32	1.94	0.01	0.60	0.14	0.02	497	0.72	0.27	563
	1.16	3.95	1.45	0.02	2.12	0.25	0.02	371	2.50	0.27	1721
	0.64	2.55	1.45	0.02	0.48	0.21	0.02	320	0.73	0.27	1986
	0.64	2.31	1.65	0.03	0.54	0.21	0.02	379	1.32	0.27	2210
	0.83	3.11	1.94	0.02	0.55	0.22	0.03	266	0.85	0.74	2567
	0.64	2.37	1.74	0.02	0.55	0.10	0.02	507	1.15	0.18	2243
	0.39	4.38	1.16	0.02	0.26	0.33	0.05	139	1.82	0.27	2264
	0.10	1.95	1.35	0.02	0.46	0.26	0.03	396	1.45	0.85	412
1.25	3.38	1.25	0.02	0.32	0.34	0.03	489	2.22	0.79	1766	
mean	0.99	3.19	1.82	0.02	0.91	0.21	0.03	404	1.65	0.34	2030
Std.	0.55	0.89	0.48	0.01	0.77	0.11	0.01	140	0.64	0.22	670

Table I-3: Results of bulk analyses for 1/2"-1" size tire chips.

ion	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
Normal- ized Concen- tration (ppm)	0.87	1.39	1.74	0.03	1.16	0.19	0.02	602	5.85	0.88	3005
	2.02	1.24	1.93	0.02	0.58	0.52	0.03	671	4.35	0.64	3072
	0.48	4.10	1.44	0.02	1.89	0.05	0.04	1125	4.33	0.80	3927
	1.06	2.87	4.84	0.02	1.21	0.15	0.05	282	4.18	0.83	2996
	1.15	6.47	2.02	0.01	1.02	0.19	0.04	261	2.11	0.80	2953
	1.25	5.91	1.83	0.02	1.05	0.21	0.04	1146	6.37	0.65	3293
	0.98	3.21	2.22	0.02	3.24	0.40	0.04	693	3.28	0.53	3120
	0.63	0.95	1.91	0.03	0.41	0.22	0.04	366	2.66	0.95	3231
	0.83	4.57	1.69	0.01	0.51	0.11	0.05	642	3.46	0.61	1222
	1.27	1.21	1.91	0.02	0.60	0.48	0.03	752	3.85	0.71	2935
	0.83	6.48	1.58	0.02	0.60	0.27	0.05	839	2.32	0.67	5309
	0.92	4.14	1.58	0.02	0.31	0.13	0.03	629	3.26	0.46	2970
	1.27	2.99	2.01	0.01	0.30	0.31	0.03	220	1.67	0.77	2981
	1.32	1.65	1.58	0.02	0.41	0.26	0.02	1198	2.99	0.66	3373
	0.83	3.72	1.68	0.02	0.71	0.24	0.03	990	2.30	0.71	3445
	0.81	1.70	0.72	0.02	0.40	0.21	0.05	647	1.53	0.71	2681
	0.82	1.09	1.47	0.01	3.05	0.28	0.04	826	1.01	0.68	5930
	1.17	1.82	3.92	0.04	0.52	0.18	0.03	877	2.99	0.80	2754
0.83	3.33	1.47	0.03	0.71	0.10	0.03	494	0.89	0.67	3644	
0.83	2.47	1.79	0.01	0.41	0.54	0.04	886	1.46	0.49	2664	
mean	1.01	3.06	1.97	0.02	0.95	0.25	0.04	707	3.04	0.70	3270
Std.	0.33	1.78	0.89	0.01	0.84	0.14	0.01	289	1.49	0.12	963

Table I-4: Results of bulk analyses for 1"-1.5" size tire chips.

ion	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
Normalized Concentration (ppm)	2.09	1.96	1.77	0.07	0.79	0.35	0.03	940	3.28	0.72	3768
	1.36	6.83	1.13	0.03	0.20	0.20	0.04	626	5.73	0.70	2514
	1.26	1.08	2.61	0.01	1.29	0.34	0.05	188	1.25	0.61	5309
	1.57	3.90	1.34	0.01	0.20	0.10	0.04	941	3.82	0.71	2919
	1.05	4.77	1.13	0.04	0.90	0.32	0.03	837	2.80	0.91	1827
	1.15	3.87	1.55	0.02	1.00	0.28	0.03	523	2.26	0.29	3510
	1.05	4.51	1.66	0.02	1.86	0.45	0.05	1361	3.43	0.87	3401
	0.84	5.63	1.34	0.03	0.82	0.16	0.04	1131	2.82	0.67	2976
	1.46	1.64	2.39	0.02	0.70	0.12	0.05	839	3.55	0.86	4474
	0.82	0.70	2.60	0.02	0.70	0.62	0.03	199	1.47	0.75	3622
	1.15	2.01	1.33	0.02	3.01	0.26	0.04	126	5.24	0.57	2990
	1.25	1.46	1.75	0.04	2.06	0.71	0.06	358	2.85	0.56	4895
	1.04	1.16	1.44	0.04	0.72	0.02	0.05	1073	5.30	0.86	2761
	0.16	1.01	1.33	0.04	0.80	0.37	0.04	137	4.48	0.89	3353
	0.84	5.51	1.23	0.01	0.91	0.11	0.04	916	2.65	0.75	2456
	1.25	3.98	1.43	0.07	1.09	0.38	0.05	632	2.65	0.74	3606
	0.81	3.17	1.23	0.05	1.05	0.07	0.05	949	3.03	0.82	2095
	0.94	2.81	1.54	0.01	1.23	0.30	0.04	1160	1.45	0.68	3071
1.25	2.29	1.43	0.05	0.70	0.40	0.04	845	0.83	0.64	2414	
1.57	5.64	1.43	0.06	0.90	0.20	0.04	849	2.00	0.76	3072	
mean	1.15	3.20	1.58	0.03	1.05	0.29	0.04	731	3.05	0.72	3250
Std.	0.39	1.85	0.45	0.02	0.64	0.18	0.01	368	1.37	0.15	885

APPENDIX J

RESULTS OF LEACHATE ANALYSIS FOR LABORATORY SAMPLES

Table J-1: Detection limit* of equipment** used for leachate analysis.

(a) data provided by manufacturer (Instrumentation Laboratory, 1982; Perkin-Elmer, 1985)

Leachate Concentration (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.023	0.0013	0.00019	0.000003	0.00002	0.00001	0.00002	0.0046	0.0014	0.00005	0.000001

(b) determined by blank sample

Leachate Concentration (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.2	0.33	0.21	0.0006	0.0006	0.0003	0.0001	0.2	0.3	0.0003	0.003

* The detection limit was three times of the standard deviation of concentration of blank sample.

** The elements of aluminum, barium, calcium, manganese, and iron were analyzed in ICP and the elements of cadmium, chromium, cobalt, copper, lead, and zinc were analyzed in GFAA.

Table J-2: Results of chemical analysis of leachate from lab samples of 1/4"-1/2" size shredded tire material.

Normalized Concentrations (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn*
0.062	3.527	1.842	0.006	0.0018	0.0018	0.0006	0.612	0.023	0.0013	2.9
0.063	3.509	2.298	0.003	0.0021	0.0029	0.0004	0.613	0.02	0.0004	3
0.102	1.162	2.195	0.002	0.0023	0.0019	0.0002	0.66	0.03	0.0012	1.5
0.04	2.921	2.298	0.002	0.0005	0.0047	0.0001	0.68	0.01	0.0016	2.2
0.037	2.294	2.092	0.003	0.0023	0.0036	0.001	0.62	0.016	0.0015	1.6
0.08	4.561	1.31	0.004	0.0031	0.0016	0.0008	0.622	0.015	0.0033	1.5
0.06	2.269	1.485	0.004	0.0020	0.0026	0.0007	0.624	0.011	0.001	1.5
0.05	2.256	1.297	0.005	0.0061	0.0014	0.0012	0.626	0.023	0.0018	1.6
0.075	4.408	1.399	0.004	0.0028	0.0019	0.0013	0.634	0.023	0.001	3.3
0.062	2.193	0.296	0.004	0.0021	0.0017	0.0009	0.636	0.023	0.0011	2.1
0.04	3.271	1.193	0.001	0.0022	0.003	0.0009	0.638	0.02	0.0019	1.1
0.061	2.169	1.795	0.0012	0.0013	0.0027	0.001	0.64	0.013	0.0024	1.4
0.062	3.226	1.193	0.001	0.0015	0.0016	0.0012	0.643	0.014	0.001	1.6
0.046	2.139	1.562	0.003	0.0014	0.001	0.0013	0.645	0.018	0.0014	3.2
0.063	3.19	1.784	0.006	0.0024	0.0016	0.0015	0.648	0.011	0.0011	2.1
0.061	3.175	1.193	0.004	0.001	0.0026	0.0006	0.649	0.022	0.0018	3.2
0.056	4.142	1.361	0.008	0.0022	0.0017	0.0009	0.658	0.01	0.0026	2.2
0.102	4.123	1.765	0.001	0.0015	0.0016	0.0014	0.66	0.01	0.0012	2.6
0.07	3.076	1.254	0.003	0.0036	0.0018	0.001	0.663	0.009	0.0021	4.1
0.08	1.02	1.845	0.006	0.0025	0.0016	0.0011	0.665	0.016	0.0008	0.7

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100.

Table J-3: Results of chemical analysis of leachate from lab samples of 1/2"-1" size shredded tire material.

Normalized Concentrations (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn*
0.057	2.949	1.705	0.0026	0.0046	0.0017	0.001	1.726	0.23	0.0028	3.6
0.032	3.912	0.924	0.0013	0.0020	0.0027	0.0011	4.684	1.23	0.0004	1.2
0.044	3.894	0.913	0.003	0.0012	0.002	0.0011	3.686	6.23	0.0003	4.5
0.031	2.906	2.004	0.0011	0.0038	0.0026	0.004	3.168	4.68	0.0008	6.9
0.04	3.853	1.506	0.0011	0.0040	0.0026	0.0001	1.936	3.7	0.0024	5.8
0.054	1.917	1.089	0.002	0.0026	0.0016	0.0003	4.694	1.6	0.0022	9.1
0.057	3.815	1.19	0.0023	0.0056	0.0017	0.0012	3.76	1.66	0.0014	2.3
0.04	1.898	1.999	0.005	0.0029	0.0037	0.0009	3.008	0.9	0.001	1.5
0.03	1.889	2.098	0.006	0.0027	0.001	0.0016	0.702	1.61	0.0025	8.7
0.04	2.821	2.9	0.0023	0.0036	0.0022	0.001	3.704	1.27	0.0045	5.6
0.062	0.923	1.389	0.0022	0.001	0.0018	0.0009	5.068	0.3	0.0034	6.2
0.039	2.756	0.189	0.0025	0.0026	0.0037	0.0008	2.007	3.02	0.0035	7.1
0.028	2.744	1.289	0.0021	0.0026	0.0021	0.001	2.013	2.61	0.0079	3.6
0.028	1.821	1.089	0.0012	0.0023	0.0009	0.0012	2.816	0.64	0.0046	5.9
0.056	1.812	2.086	0.0011	0.0022	0.0014	0.002	3.245	0.7	0.001	7.8
0.057	2.706	0.987	0.002	0.0025	0.0036	0.001	3.272	1.36	0.0014	6.4
0.02	1.796	1.484	0.004	0.0003	0.0011	0.0013	1.614	2.36	0.0037	6.7
0.036	2.681	2.978	0.003	0.0022	0.0021	0.0012	3.733	6.2	0.0042	6.7
0.046	1.779	1.98	0.0021	0.0013	0.0011	0.0011	2.964	3.4	0.0059	6.3
0.036	1.771	1.188	0.002	0.0013	0.0006	0.0008	2.384	3.01	0.0024	5.9

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100.

Table J-4: Results of chemical analysis of leachate from lab samples of 1"-1.5" size shredded tire material.

Normalized Concentrations (ppm)										
Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn*
0.0394	2.275	0.885	0.0015	0.0028	0.0012	0.0007	3.503	1.67	0.0019	6.2
0.029	1.773	2.488	0.0011	0.0035	0.0012	0.0009	4.828	3.26	0.0029	7.7
0.038	1.819	2.185	0.0016	0.003	0.0015	0.0013	3.503	0.9	0.002	1.3
0.026	2.084	2.684	0.0013	0.0037	0.0022	0.001	5.126	0.199	0.0013	0.7
0.054	1.389	1.183	0.005	0.0017	0.0012	0.001	5.841	0.82	0.0025	6.5
0.04	2.692	0.783	0.003	0.002	0.003	0.001	5.402	9.02	0.006	8.9
0.033	1.3	2.02	0.0021	0.0023	0.001	0.0012	2.611	6.87	0.001	9
0.027	1.23	1.283	0.002	0.0013	0.0025	0.0013	3.736	0.198	0.0016	2.3
0.031	1.102	1.482	0.004	0.0040	0.0037	0.0006	4.214	0.99	0.0014	6.5
0.023	1.02	0.382	0.0016	0.0058	0.0022	0.0005	4.201	1.38	0.0007	4.3
0.0392	2.54	1.276	0.0017	0.0021	0.0022	0.0012	3.915	3.02	0.008	6.5
0.066	1.323	0.878	0.0018	0.0022	0.0036	0.001	3.713	0.197	0.0016	2.1
0.052	0.626	0.48	0.006	0.0015	0.0015	0.0011	3.02	1.85	0.003	3.4
0.021	0.89	2.083	0.0012	0.0030	0.0025	0.0011	2.87	1.27	0.0021	3.9
0.047	1.607	1.174	0.0021	0.0041	0.0033	0.0012	4.902	3.06	0.004	8.1
0.031	0.664	1.281	0.0014	0.0021	0.0022	0.0018	7.6	2.11	0.0024	9.1
0.039	1.162	1.074	0.002	0.0020	0.0019	0.0013	8.598	6.54	0.0038	7
0.032	1.255	0.677	0.0012	0.0026	0.0015	0.0007	7.195	3.02	0.0021	3.9
0.034	0.689	1.271	0.006	0.0027	0.0021	0.0006	1.3	3.79	0.0024	4.5
0.042	1.518	1.27	0.0011	0.0016	0.0017	0.0008	1.69	1.68	0.0018	6.5

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100.

APPENDIX K

RESULTS OF LEACHATE ANALYSIS FOR FIELD SAMPLES

Table K-1: Detection limit* of the equipment** used for analysis of leachate from box samples.

(a) data provided by manufacturer (Instrumentation Laboratory, 1982)

Leachate Concentration (ppm)									
Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.023	0.0013	0.0027	0.0060	0.0071	0.0054	0.0046	0.0014	0.00005	0.0018

(b) determined by blank sample

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0.036	0.26	0.21	0.1	0.03	0.08	0.036	0.21	0.3	0.0003	0.6
6/7/95	0.036	0.26	0.21	0.1	0.03	0.08	0.036	0.21	0.3	0.0003	0.6
7/7/95	0.036	0.26	0.21	0.1	0.03	0.08	0.036	0.21	0.3	0.0003	0.6
8/2/95	0.21	0.3	0.21	0.06	0.02	0.13	0.02	0.24	0.27	0.0003	0.3
8/23/95	0.21	0.3	0.21	0.06	0.02	0.13	0.02	0.24	0.27	0.0003	0.3
9/17/95	0.21	0.3	0.21	0.06	0.02	0.13	0.02	0.24	0.27	0.0003	0.3
10/20/95	0.21	0.3	0.21	0.06	0.02	0.13	0.02	0.24	0.27	0.0003	0.3
11/21/95	0.21	0.3	0.21	0.06	0.02	0.13	0.02	0.24	0.27	0.0003	0.3
3/20/96	0.2	0.3	0.2	0.03	0.02	0.09	0.02	0.3	0.2	0.0003	0.2
4/18/96	0.2	0.3	0.2	0.03	0.02	0.09	0.02	0.3	0.2	0.0003	0.2
5/1/96	0.2	0.3	0.2	0.03	0.02	0.09	0.02	0.3	0.2	0.0003	0.2
5/17/96	0.2	0.3	0.2	0.03	0.02	0.09	0.02	0.3	0.2	0.0003	0.2
6/3/96	0.2	0.3	0.2	0.03	0.02	0.09	0.02	0.3	0.2	0.0003	0.2
6/16/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
7/17/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
7/29/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
8/18/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
8/28/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
9/18/96	0.2	0.33	0.21	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45

* The detection limit was three times of the standard deviation of concentration of blank sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-2: Precision* of the equipment** used for analysis of leachate from box samples containing pure shredded tire (1/4"-1/2") material.

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0	0.09	0.21	0.001	0.021	0.002	0	0	0	0.0006	0
6/7/95	0.03	0.12	0.81	0.001	0.01	0.002	0.003	0.21	0.03	0.0003	0.12
7/7/95	0.021	0.12	0.21	0	0.003	0.002	0.004	0	0	0.0006	0
8/2/95	0	0.09	0	0.001	0.009	0.005	0.002	0	0.06	0.00036	0
8/23/95	0	0.156	0.21	0.001	0.021	0.006	0.002	0	0	0.0006	0.21
9/17/95	0	0.12	0.21	0.001	0	0.018	0	0.15	0.1	0.0003	0.39
10/20/95	0.015	0.15	0.21	0	0.021	0.021	0	0.24	0.1	0.0003	0.18
11/21/95	0.03	0.15	0.09	0.002	0.021	0.012	0.003	0.33	0	0.0003	0.3
3/20/96	0	0.18	0.15	0	0.005	0.009	0	0.21	0	0.00045	0.24
4/18/96	0.01	0.036	0.21	0.001	0.005	0.004	0.002	0	0	0.0009	0
5/1/96	0	0.267	0	0	0.009	0.006	0.002	0	0	0.0009	0
5/17/96	0.021	0.273	0	0.003	0.01	0.003	0.001	0.21	0.06	0.0006	0.12
6/3/96	0	0.186	0.21	0	0.021	0.004	0	0.21	0	0.00036	0
6/16/96	0.021	0.282	0.21	0.001	0.01	0	0	0.21	0.09	0.00045	0.39
7/17/96	0.012	0.051	0.15	0.001	0.021	0.021	0.001	0.21	0.03	0.0006	0.21
7/29/96	0.01	0.15	0.063	0	0	0.001	0	0	0	0.0003	0.15
8/18/96	0.03	0.12	0.21	0.001	0.006	0.021	0.001	0.45	0.03	0.0003	0.21
8/28/96	0.03	0.186	0.09	0	0.021	0.001	0.001	0.27	0.024	0.00072	0.3
9/18/96	0.015	0.21	0.12	0.001	0.006	0	0	0.39	0.027	0.00039	0.18

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-3: Precision* of the equipment** used for analysis of leachate from box samples containing pure shredded tire (1/2"-1") material.

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0.009	0.09	0.69	0.002	0.003	0.005	0	0.99	0.3	0.00012	0.9
6/7/95	0.021	0.03	0.21	0.001	0.002	0	0.002	0.15	0.24	0.0006	0.54
7/7/95	0	0.12	0.21	0.003	0.004	0	0.003	0.21	0.21	0.0003	0.33
8/2/95	0.021	0.1	0.21	0.001	0.004	0.001	0.003	0	0.306	0.0003	0.18
8/23/95	0.003	0.12	0.21	0	0.003	0.002	0.002	0.9	0.18	0.0006	0.78
9/17/95	0.018	0.138	0.21	0.003	0	0.003	0	0.12	0.21	0.00012	0.36
10/20/95	0	0.186	0.09	0	0.002	0.005	0.002	0.21	0.15	0.0003	0.06
11/21/95	0.021	0.063	0.21	0.003	0	0.004	0	0.21	0.18	0.0006	0.09
3/20/96	0.021	0.09	0	0	0	0	0.002	0.21	0.075	0.00012	0.36
4/18/96	0	0.006	0.21	0.001	0.002	0.001	0	0.6	0.06	0.00015	0.3
5/1/96	0.018	0.06	0.09	0.002	0	0.001	0.003	0.24	0.045	0.00021	0.21
5/17/96	0.018	0.069	0.12	0.003	0.001	0	0.002	0.15	0.21	0.0006	0.18
6/3/96	0.006	0.09	0.18	0	0.001	0.006	0.001	0.21	0.36	0.0002	0.24
6/16/96	0.012	0.099	0.09	0.003	0	0.003	0	0.09	0.24	0.00015	0.24
7/17/96	0.009	0.024	0.12	0.001	0	0.001	0.001	0.06	0.3	0.0003	0.09
7/29/96	0.006	0.045	0.18	0.004	0.001	0.003	0	0.03	0.12	0.00015	0.6
8/18/96	0.012	0.024	0.09	0.002	0.001	0	0.001	0.024	0.03	0.00011	0.27
8/28/96	0.018	0.021	0.15	0.001	0	0.005	0	0.06	0.06	0.0003	0.12
9/18/96	0.006	0.021	0.21	0	0.001	0.006	0	0.021	0.036	0.00024	0.18

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-4: Precision* of the equipment** used for analysis of leachate from box samples containing pure shredded tire (1"-1.5") material.

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0.006	0.09	0.6	0.001	0.006	0	0.009	0.78	0.09	0.00024	0.63
6/7/95	0	0.045	0.18	0	0.003	0.006	0	0.036	0.03	0.00075	0.18
7/7/95	0.003	0.03	0.12	0.001	0	0.003	0.006	0.51	0.045	0.00018	0.06
8/2/95	0.001	0.09	0.27	0	0.003	0.009	0.006	0.021	0	0.00024	0.09
8/23/95	0	0.081	0.21	0.002	0.009	0	0.012	0.21	0.06	0.00021	0.45
9/17/95	0	0.027	0.108	0.002	0	0.002	0.003	0.6	0.03	0.00033	0.18
10/20/95	0.003	0.105	0.6	0.002	0.012	0.003	0.006	0.24	0.021	0.00045	0.12
11/21/95	0.002	0.138	0.12	0.001	0.006	0.004	0	0.09	0.15	0.0006	0.21
3/20/96	0.002	0.201	0.063	0.003	0.003	0.002	0.021	0.018	0.06	0.00012	0.36
4/18/96	0.001	0.186	0.3	0.002	0.012	0.009	0.015	0.3	0	0.00009	0.75
5/1/96	0.003	0.09	0.15	0.001	0.003	0.008	0.006	0.45	0.12	0.00009	0.33
5/17/96	0.006	0.03	0.18	0	0.006	0.003	0.003	0.45	0.045	0.00003	0.45
6/3/96	0.001	0.045	0.117	0.003	0.009	0.003	0.009	0.045	0.3	0.00012	0.99
6/16/96	0	0.108	0.132	0.001	0	0	0.003	0.21	0.009	0.0003	0.54
7/17/96	0.006	0.09	0.255	0	0.009	0.006	0	0.3	0.12	0.00009	0.63
7/29/96	0.001	0.33	0.6	0.001	0.006	0.006	0	0.18	0	0.00009	0.27
8/18/96	0	0.159	0.279	0.002	0.009	0.008	0.009	0.108	0.027	0.00012	0.3
8/28/96	0.003	0.12	0.24	0.003	0.003	0	0.006	0.6	0.21	0.00006	0.24
9/18/96	0.003	0.159	0.18	0.001	0.003	0.006	0	0.18	0.09	0.00018	0.33

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-5: Precision* of the equipment** used for analysis of leachate from box samples containing soil-tire mixtures (70% silt with 30% 1/4"-1/2" size shredded tire material).

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0.03	0.012	0.21	0.001	0.003	0.009	0.001	0.78	0.06	0.0003	0.15
6/7/95	0.01	0.015	0.9	0.001	0.009	0	0	0.09	0.15	0.0006	0.3
7/7/95	0.02	0.009	0.6	0	0.006	0.006	0.003	0.45	0.09	0	0.021
8/2/95	0.03	0.015	0.24	0.001	0	0.009	0.002	0.21	0.03	0.0003	0.099
8/23/95	0	0.012	0.201	0	0.009	0.006	0.003	0.18	0.03	0.000201	0.018
9/17/95	0	0.024	0.21	0.001	0.003	0	0.006	0.6	0.078	0.0006	0.15
10/20/95	0.027	0.021	0.21	0.001	0.001	0.01	0	0.09	0.21	0.000117	0.21
11/21/95	0.033	0.021	0.135	0	0.003	0.009	0.006	0.24	0.09	0	0.3
3/20/96	0.03	0	0.3	0.001	0	0	0.003	0.39	0.09	0.0003	0.21
4/18/96	0.024	0.021	0.09	0	0.003	0.006	0	0.12	0.06	0	0.3
5/1/96	0.006	0.018	0.15	0	0.006	0.006	0.009	0.21	0.21	0.0003	0
5/17/96	0.009	0.012	0.3	0	0.009	0	0.009	0.33	0.18	0.0003	0.162
6/3/96	0.021	0.015	0.21	0	0	0.003	0.006	0.39	0.15	0.0006	0.21
6/16/96	0.009	0.024	0.45	0.001	0.003	0.006	0.003	0.18	0.21	0.000201	0.21
7/17/96	0.018	0.03	0.099	0	0	0	0.006	0.3	0.18	0.000168	0.03
7/29/96	0.015	0.03	0.21	0	0.009	0.003	0	0.3	0.09	0	0.18
8/18/96	0.03	0.024	0.45	0	0.009	0.003	0	0.33	0.09	0	0.21
8/28/96	0.021	0.033	0.21	0	0.003	0.006	0.009	0.06	0.21	0.0003	0.18
9/18/96	0.018	0.018	0.9	0.001	0.006	0.009	0.009	0.27	0.09	0.0003	0.15

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-6: Precision* of the equipment** used for analysis of leachate from box samples containing soil-tire mixtures (70% clay with 30% 1/4"-1/2" size shredded tire material).

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0.012	0	0.18	0	0.009	0.006	0.009	0.69	0.15	0.00009	0.21
6/7/95	0.03	0.006	0.18	0	0.006	0	0	0.33	0.12	0.00009	0.33
7/7/95	0.015	0.003	0.09	0	0.006	0	0.003	0.24	0	0.00021	0.63
8/2/95	0.021	0.018	0.09	0.001	0.006	0.003	0.006	0.48	0.18	0	0.36
8/23/95	0.066	0.009	0.12	0	0.009	0.003	0	0.45	0.09	0.000168	0.45
9/17/95	0.045	0.003	0.03	0.001	0.006	0.006	0.009	0.33	0.21	0.000192	0.18
10/20/95	0.024	0.06	0.21	0	0.003	0.009	0.003	0.21	0.06	0.0003	0.24
11/21/95	0.018	0.06	0.06	0	0.009	0.003	0.006	0.48	0.21	0	0.21
3/20/96	0.018	0.06	0.09	0	0.006	0.009	0	0.75	0.18	0.0003	0.36
4/18/96	0.06	0.021	0.18	0.001	0.009	0.006	0.009	0.6	0.18	0	0.21
5/1/96	0.069	0.06	0.18	0	0	0.009	0.003	0.27	0.06	0	0.3
5/17/96	0.006	0.078	0.15	0	0.006	0.006	0.006	0.54	0.09	0.00024	0.45
6/3/96	0.012	0.09	0.21	0	0.006	0	0	0.6	0.03	0.00021	0.18
6/16/96	0.012	0.045	0.09	0	0	0.003	0.009	0.18	0	0.000201	0.6
7/17/96	0.012	0.03	0.15	0.001	0.009	0	0.006	0.48	0.06	0.000135	0.3
7/29/96	0.012	0.039	0.189	0	0.006	0.009	0	0.33	0.12	0.00024	0.15
8/18/96	0.009	0.039	0.18	0	0.009	0.006	0.001	0.3	0	0.000198	0.24
8/28/96	0.015	0.06	0.21	0.001	0.003	0.003	0.003	0.45	0.18	0	0.18
9/18/96	0.021	0.033	0.12	0.001	0.006	0	0.009	0.24	0.21	0.0003	0.21

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-7: Precision* of the equipment** used for analysis of leachate from box samples containing soil-tire mixtures (40% clay with 60% 1/4"-1/2" size shredded tire material).

Collecting Date	Leachate Concentration (ppm)										
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
5/19/95	0	0.06	0.18	0	0.001	0.003	0	0.27	0.18	0.0006	0.15
6/7/95	0.009	0	0.12	0.001	0.003	0	0.001	0.21	0.15	0.0003	0.09
7/7/95	0.012	0.1	0.18	0	0	0	0.003	0.3	0.09	0.00024	0.3
8/2/95	0.018	0.12	0.21	0.001	0.003	0.006	0.006	0.15	0	0.00012	0.36
8/23/95	0.021	0.09	0.3	0	0.006	0.009	0	0.63	0.12	0.0003	0.48
9/17/95	0.018	0.21	0.033	0.001	0	0.002	0.003	0.42	0.12	0.0006	0.54
10/20/95	0.021	0.21	0.24	0	0	0.001	0.001	0.21	0.15	0.0003	0.42
11/21/95	0	0	0.21	0.001	0.003	0.009	0	0.69	0.21	0.00012	0.24
3/20/96	0.018	0.33	0.03	0	0.001	0.009	0.003	0.48	0.18	0.00018	0.33
4/18/96	0.024	0.21	0.18	0.001	0.003	0	0.006	0.24	0.09	0.0009	0.21
5/1/96	0.015	0.24	0.12	0.001	0	0.006	0	0.45	0.15	0.0003	0.33
5/17/96	0.012	0.39	0.3	0	0.003	0.003	0.003	0.27	0.12	0.0006	0.33
6/3/96	0.015	0.252	0.063	0.001	0.003	0.006	0.003	0.45	0.18	0.0003	0.6
6/16/96	0.012	0.198	0.099	0.001	0	0	0.003	0.18	0.09	0.0006	0.51
7/17/96	0	0.33	0.21	0	0.003	0.009	0.006	0.39	0.24	0.0003	0.99
7/29/96	0.024	0.3	0.27	0	0	0.006	0.003	0.42	0.06	0.0003	0.72
8/18/96	0.021	0.36	0.3	0	0.006	0.009	0.003	0.33	0.09	0.0003	0.45
8/28/96	0.03	0.27	0.33	0.001	0.001	0	0.001	0.6	0.21	0.0003	0.36
9/18/96	0.012	0.24	0.18	0	0.003	0.009	0	0.54	0.18	0.0006	0.78

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, calcium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed in ICP and the element of lead were analyzed in GFAA.

Table K-8: Chemical composition of the leachate from box samples containing shredded tire (1/4"-1/2") material.

Collecting Date	Leachate Concentration (ppm)											Temp	pH
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn		
5/19/95	0	0	30.3	0	0	0	0	0	0	0	8.25	15	7.1
6/7/95	0	0	39.5	0	0	0	0	0	0	0	9.85	21	7.1
7/7/95	0	0	38.6	0	0	0	0	0	0	0	10.56	24	6.9
8/2/95	0.26	1.01	37.4	0.001	0.02	0.01	0.01	1.17	0.3	0.001	13.87	28	7.1
8/23/95	0.33	1.62	38.6	0.002	0.03	0.01	0.01	1.25	0.33	0.0012	15.24	24	7.4
9/17/95	0.40	1.82	39.6	0.002	0.04	0.01	0.02	1.33	0.5	0.0014	16.00	20	7.2
10/20/95	0.44	2.15	40.9	0.002	0.04	0.02	0.02	1.37	0.73	0.0015	16.32	13	7.1
11/21/95	0.40	2.51	45.9	0.001	0.05	0.03	0.03	1.42	0.5	0.0018	18.05	4	6.9
3/20/96	0.42	2.60	40.2	0	0.11	0.06	0.05	1.41	0.4	0.002	18.90	11	6.9
4/18/96	0.40	2.70	38.2	0	0.08	0.09	0.03	1.38	0.4	0.002	19.57	16	6.8
5/1/96	0.41	2.76	37.9	0	0.05	0.07	0.02	1.40	0.4	0.0015	17.10	18	6.8
5/17/96	0.38	2.80	38.8	0.004	0.04	0.05	0	1.47	0.35	0.001	16.24	18	6.8
6/3/96	0.41	2.84	38.0	0.001	0.04	0.05	0.03	1.50	0.25	0.001	16.53	20	6.7
6/16/96	0.39	2.72	40.2	0.002	0.03	0.05	0.02	1.49	0.2	0.0011	16.02	21	6.8
7/17/96	0.32	2.80	38.3	0	0.02	0.03	0	1.64	0.2	0.001	15.36	26	6.8
7/29/96	0.35	2.57	36.2	0	0.019	0.04	0.01	1.70	0.2	0.001	15.35	26	6.8
8/18/96	0.41	2.42	35.4	0.002	0.006	0.03	0.01	1.81	0.21	0.0007	15.23	24	6.9
8/28/96	0.36	2.32	35.6	0	0.006	0.02	0.02	1.70	0.18	0.0008	15.30	24	6.9
9/18/96	0.40	2.30	35.1	0.001	0.006	0.02	0.02	1.58	0.1	0	15.40	20	6.8

 Insignificant data because the concentration is below the detection limit.

Table K-9: Chemical composition of the leachate from box samples containing shredded tire (1/2"-1") material.

Collecting Date	Leachate Concentration (ppm)											Temp	pH
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn		
5/19/95	0	0	20.1	0	0	0	0	7.21	0	0	8.1	15	6.9
6/7/95	0	0	25.9	0	0	0	0	6.59	0	0	10.9	21	6.9
7/7/95	0	0	29.7	0	0	0	0	6.06	0	0	11.3	24	7.1
8/2/95	0.26	1.84	29.3	0.003	0.01	0.01	0.01	5.97	0.91	0.003	12.17	28	7.1
8/23/95	0.31	1.82	26.2	0.001	0.02	0.03	0.01	6.05	1.52	0.0028	21.51	24	7.4
9/17/95	0.31	1.72	25.7	0.002	0.04	0.02	0.01	5.90	2.06	0.0029	21.9	20	7.3
10/20/95	0.29	1.89	24.5	0.001	0.05	0.01	0.01	6.06	2.62	0.003	22.5	13	7.1
11/21/95	0.29	2.09	21.4	0	0.06	0.02	0.01	6.03	3.04	0.0029	22.03	4	7.1
3/20/96	0.29	2.16	21.4	0.001	0.1	0.03	0.01	6.1	1.56	0.0028	21.31	11	6.9
4/18/96	0.29	2.11	21.1	0	0.08	0.05	0.02	5.92	1.25	0.003	21.32	16	6.7
5/1/96	0.27	2.12	21.4	0.001	0.06	0.03	0.02	5.99	0.30	0.0025	21.41	18	6.8
5/17/96	0.28	2.14	21.4	0.001	0.04	0.06	0.02	6.00	0.20	0.0023	20.89	18	6.8
6/3/96	0.27	2.13	21.1	0	0.04	0.05	0	6.02	0.15	0.0017	20.44	20	6.8
6/16/96	0.29	2.13	21.1	0	0.03	0.05	0	5.96	0.12	0.0018	20.21	21	6.8
7/17/96	0.29	2.13	20.9	0.001	0.03	0.05	0.02	5.97	0.15	0.0018	19.99	26	6.7
7/29/96	0.31	1.89	20.9	0.002	0.03	0.04	0.02	5.86	0.10	0.0017	20.03	26	6.8
8/18/96	0.3	1.97	21	0.002	0.02	0.05	0.01	6.02	0.10	0.0014	20.09	24	6.9
8/28/96	0.28	1.63	21.1	0.001	0.02	0.04	0.01	5.99	0.10	0.001	19.96	24	6.8
9/18/96	0.29	1.63	21	0.001	0	0.03	0.01	5.91	0.15	0.001	19.93	20	6.8

 Insignificant data because the concentration is below the detection limit.

Table K-10: Chemical composition of the leachate from box samples containing shredded tire (1"-1.5") material.

Collecting Date	Leachate Concentration (ppm)											Temp	pH
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn		
5/19/95	0	0	21.5	0	0	0	0	0	0	0	18.00	15	7.1
6/7/95	0	0	29.6	0	0	0	0	0	0.89	0.001	24.00	21	6.9
7/7/95	0	0	32.4	0	0	0	0	3.46	1.00	0.001	27.28	24	6.9
8/2/95	0.20	1.02	33.6	0.003	0.04	0.01	0.01	5.38	1.66	0.003	29.61	28	7.1
8/23/95	0.24	1.03	30.0	0.001	0.08	0.02	0	6.11	3.38	0.005	32.73	24	7.2
9/17/95	0.36	1.16	26.4	0.002	0.07	0.02	0.01	7.50	2.12	0.006	29.55	20	7.2
10/20/95	0.44	1.39	23.6	0.003	0.08	0.01	0.01	6.80	1.93	0.007	26.17	13	7.1
11/21/95	0.35	1.44	19.1	0.002	0.10	0.02	0.01	5.90	1.24	0.004	24.65	4	6.9
3/20/96	0.10	1.50	18.2	0.001	0.12	0.01	0	5.65	1.03	0.001	23.18	11	6.9
4/18/96	0.06	1.62	17.1	0.001	0.13	0.07	0	5.58	0.93	0.001	23.17	16	6.7
5/1/96	0.06	1.80	16.9	0.001	0.11	0.07	0	5.58	0.84	0.001	23.17	18	6.8
5/17/96	0.04	2.09	14.6	0.002	0.11	0.06	0.01	5.60	0.75	0.0001	23.08	18	6.8
6/3/96	0.04	1.68	11.2	0.001	0.11	0.04	0.01	5.56	0.66	0	22.89	20	6.8
6/16/96	0	1.44	10.9	0.003	0.10	0.01	0.01	5.65	0.32	0	22.88	21	6.8
7/17/96	0	1.39	10.9	0.001	0.06	0	0	5.57	0.32	0	22.82	26	6.8
7/29/96	0	1.06	10.9	0	0.06	0	0	5.60	0.33	0	22.91	26	6.7
8/18/96	0	0.82	10.0	0.001	0.06	0.01	0	5.60	0.3	0	23.00	24	6.8
8/28/96	0.02	0.86	10.3	0.002	0.05	0.01	0.01	5.59	0.36	0	22.97	24	6.8
9/18/96	0	0.90	10.1	0	0.06	0.01	0	5.57	0.34	0	22.94	20	6.7

 Insignificant data because the concentration is below the detection limit.

Table K-11: Chemical composition of the leachate from box samples containing soil-tire mixtures (70% silt with 30% 1/4"-1/2" size shredded tire material).

Collecting Date	Leachate Concentration (ppm)											Temp	pH
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn		
5/19/95	0.02	0	415.41	0	0	0	0	1.01	0.26	0	1.91	15	6.8
6/7/95	0.04	0	468.00	0	0	0	0	1.16	0.29	0	1.84	21	6.7
7/7/95	0.05	0	452.10	0	0	0	0	1.14	0.30	0.001	1.84	24	6.8
8/2/95	0.04	0.43	609.21	0.002	0.06	0.04	0.01	1.22	0.34	0.001	1.80	28	7.1
8/23/95	0.08	0.42	737.58	0	0.05	0.03	0.01	1.24	0.33	0.001	1.86	24	6.9
9/17/95	0.08	0.51	570.00	0	0.04	0.03	0.01	1.19	0.38	0.001	1.81	20	6.8
10/20/95	0.08	0.54	579.41	0.002	0.03	0.04	0.01	1.12	0.42	0.001	1.82	13	6.6
11/21/95	0.1	0.75	577.24	0.001	0.03	0.04	0.01	1.08	0.45	0.001	1.84	4	6.7
3/20/96	0.11	1.05	570.00	0.001	0.03	0.03	0.01	1.09	0.31	0.001	1.93	11	6.7
4/18/96	0.17	0.98	577.12	0.001	0.03	0.02	0	1.07	0.23	0.001	1.86	16	6.6
5/1/96	0.2	1.00	581.00	0.002	0.04	0.02	0	1.06	0.20	0.001	1.90	18	6.6
5/17/96	0.24	1.02	590.40	0.003	0.04	0.02	0.01	1.07	0.23	0.001	1.86	18	6.8
6/3/96	0.29	0.96	592.50	0.002	0.03	0.03	0.01	1.06	0.21	0.001	1.91	20	6.9
6/16/96	0.33	0.85	587.51	0	0.03	0.01	0.01	1.06	0.23	0.001	1.86	21	6.9
7/17/96	0.22	0.8	594.64	0	0.03	0.01	0	1.05	0.21	0.001	1.92	26	6.8
7/29/96	0.22	0.7	581.70	0	0.02	0.01	0	1.05	0.21	0.001	1.86	26	6.8
8/18/96	0.21	0.64	583.00	0	0.01	0.01	0	1.00	0.20	0.001	1.86	24	6.8
8/28/96	0.2	0.27	586.25	0	0.01	0.01	0.01	0.80	0.23	0.001	1.82	24	6.8
9/18/96	0.2	0.41	590.32	0	0.01	0.01	0.01	0.80	0.21	0.001	1.91	20	6.8

 Insignificant data because the concentration is below the detection limit.

Table K-12: Chemical composition of the leachate from box samples containing soil-tire mixtures (70% clay with 30% 1/4"-1/2" size shredded tire material).

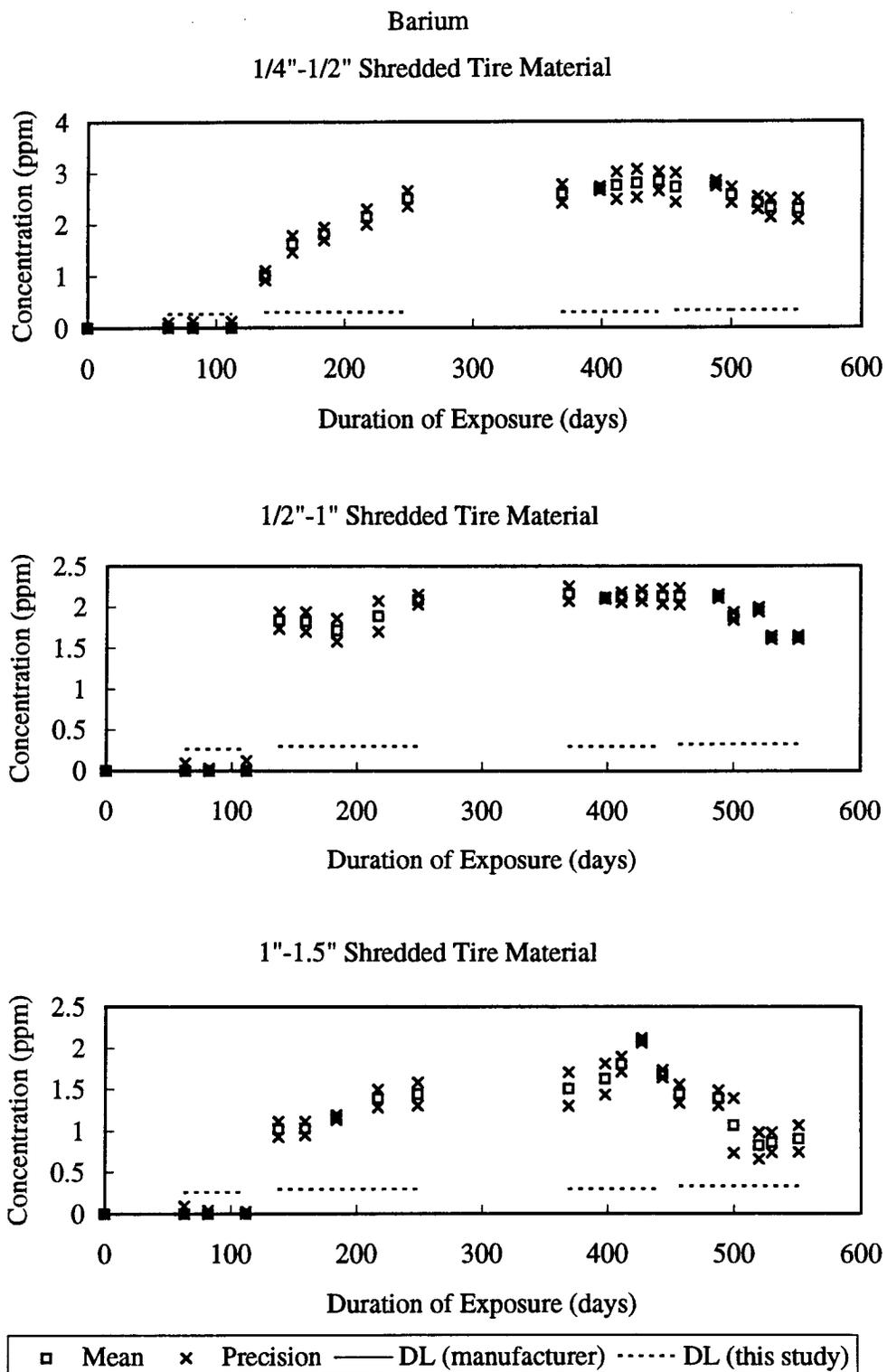
Collecting Date	Leachate Concentration (ppm)											Temp	pH
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn		
5/19/95	0.01	0	502.00	0	0	0.02	0	1.20	0.15	0	6.12	15	6.8
6/7/95	0.01	0.01	530.00	0	0	0.01	0	1.65	0.2	0	6.05	21	6.8
7/7/95	0.02	0.01	621.31	0	0.01	0.01	0	2.45	0.1	0	6.09	24	6.9
8/2/95	0.15	0.01	668.26	0.001	0	0.03	0	2.69	0.16	0	5.25	28	6.8
8/23/95	0.36	0.02	616.00	0	0	0.02	0	2.68	0.29	0	4.82	24	6.7
9/17/95	0.36	0.03	602.00	0	0.01	0.03	0	3.06	0.28	0	4.68	20	6.6
10/20/95	0.38	0.03	601.00	0	0.03	0.04	0	2.34	0.28	0	4.61	13	6.4
11/21/95	0.34	0.03	626.13	0	0.04	0.03	0	2.35	0.34	0	4.37	4	6.6
3/20/96	0.32	0.46	640.01	0	0.04	0.05	0	2.11	0.35	0	4.24	11	6.7
4/18/96	0.30	0.57	597.40	0.001	0.05	0.007	0	1.21	0.42	0	4.34	16	6.8
5/1/96	0.30	0.68	598.00	0.001	0.04	0.006	0	1.20	0.41	0	4.29	18	6.8
5/17/96	0.26	0.79	593.60	0	0.03	0.06	0	1.10	0.32	0	4.33	18	6.7
6/3/96	0.25	0.77	593.60	0	0.03	0.06	0	1.10	0.33	0	4.29	20	6.7
6/16/96	0.21	0.71	561.41	0	0.03	0.04	0	0.81	0.26	0	4.31	21	6.7
7/17/96	0.20	0.64	564.03	0	0.03	0.03	0	0.80	0.24	0	4.30	26	6.6
7/29/96	0.24	0.60	565.54	0.001	0.03	0.03	0	0.80	0.24	0	4.28	26	6.8
8/18/96	0.23	0.55	564.01	0.001	0.02	0.02	0	0.80	0.16	0	4.29	24	6.6
8/28/96	0.20	0.52	569.53	0	0.01	0.02	0	0.80	0.14	0	4.29	24	6.7
9/18/96	0.20	0.41	568.61	0.001	0.01	0.02	0	0.40	0.13	0	4.32	20	6.8

 Insignificant data because the concentration is below the detection limit.

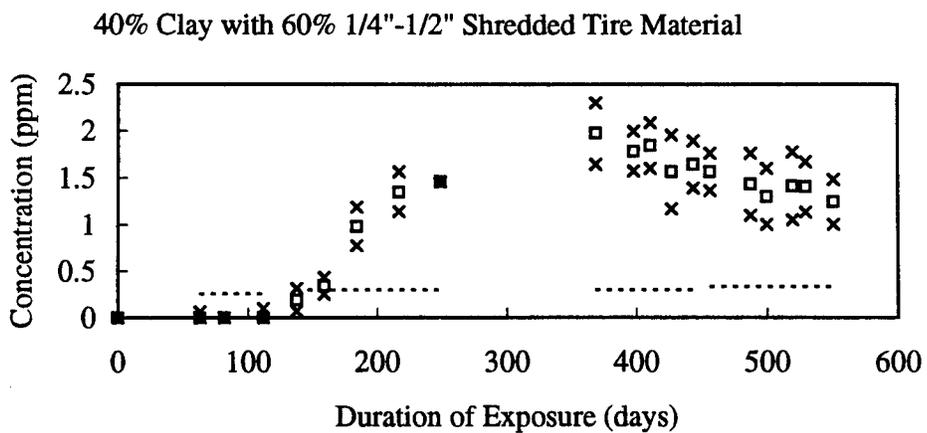
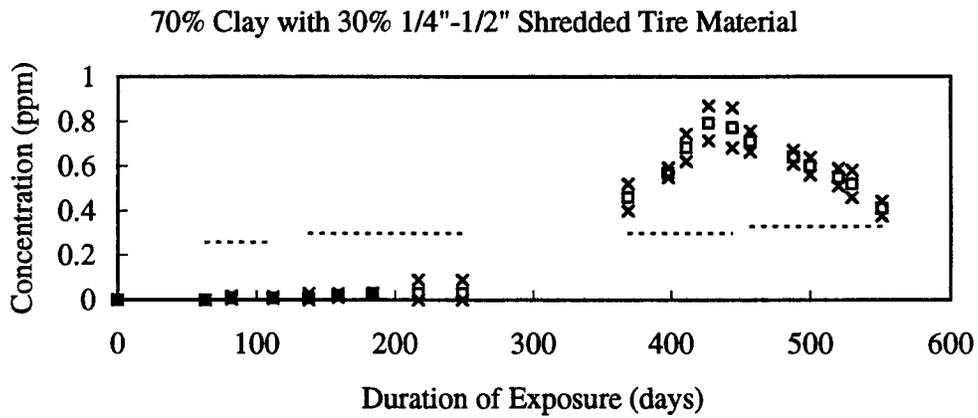
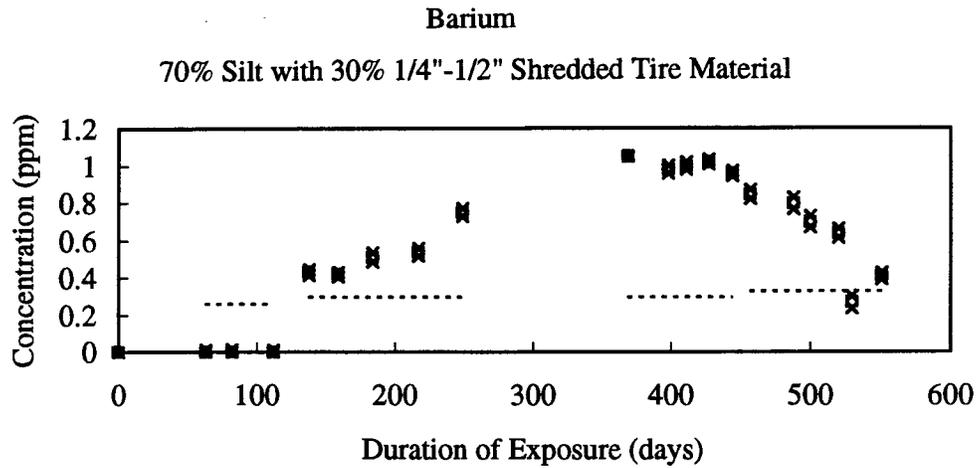
Table K-13: Chemical composition of the leachate from box samples containing soil-tire mixtures (40% clay with 60% 1/4"-1/2" size shredded tire material).

Collecting Date	Leachate Concentration (ppm)											Temp	pH	
	Al	Ba	Ca	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn			
5/19/95	0.03	0	50.23	0	0	0.01	0	0	0	0	0	3.63	15	6.9
6/7/95	0.05	0	60.80	0	0	0.01	0	0.63	0	0	0	6.03	21	6.9
7/7/95	0.05	0	62.74	0	0	0.01	0	1.02	0.1	0	0	7.52	24	6.9
8/2/95	0.05	0.19	212.25	0.001	0.01	0.01	0.01	1.31	0.32	0	0	7.65	28	7.1
8/23/95	0.09	0.34	280.94	0.001	0.02	0.03	0.01	1.59	0.4	0.001	0	7.60	24	7.1
9/17/95	0.10	0.98	260.30	0.001	0.03	0.02	0	1.98	0.52	0.001	0	7.20	20	7.1
10/20/95	0.12	1.35	253.09	0	0.03	0.02	0	2.02	0.53	0.002	0	7.35	13	6.9
11/21/95	0.14	1.46	244.24	0.001	0.03	0.02	0	2.06	0.58	0.002	0	6.83	4	6.6
3/20/96	0.30	1.97	248.06	0.002	0.03	0.03	0.04	2.12	0.52	0.002	0	5.91	11	6.7
4/18/96	0.32	1.78	241.37	0.002	0.04	0.04	0.03	1.95	0.46	0.002	0	5.24	16	6.8
5/1/96	0.20	1.84	246.23	0.003	0.03	0.03	0.03	1.94	0.41	0.002	0	5.03	18	6.9
5/17/96	0.11	1.56	241.62	0.003	0.03	0.01	0.03	1.85	0.4	0.002	0	4.80	18	6.8
6/3/96	0.09	1.64	242.15	0.002	0.02	0.02	0.02	1.71	0.36	0.002	0	4.63	20	6.7
6/16/96	0.10	1.56	232.47	0.001	0.02	0.02	0.01	1.67	0.33	0.002	0	4.41	21	6.8
7/17/96	0.10	1.43	249.62	0	0.02	0.01	0.01	1.60	0.33	0.001	0	4.27	26	6.8
7/29/96	0.10	1.30	248.40	0	0.02	0	0	1.49	0.25	0.001	0	4.21	26	6.7
8/18/96	0.10	1.41	236.60	0	0.02	0.01	0	1.36	0.2	0.001	0	4.26	24	6.6
8/28/96	0.10	1.40	249.00	0.001	0.02	0.01	0.01	1.31	0.11	0.001	0	4.16	24	6.7
9/18/96	0.10	1.24	241.30	0	0.01	0.02	0.01	1.31	0.03	0.001	0	4.20	20	6.7

 Insignificant data because the concentration is below the detection limit.

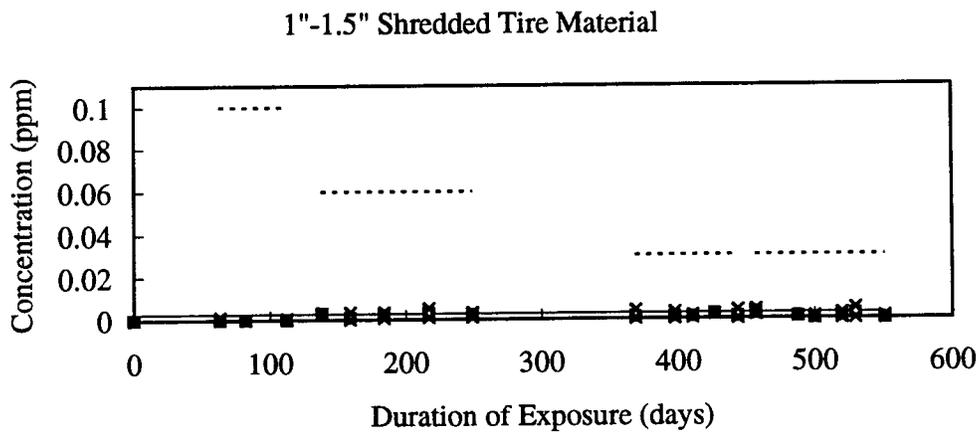
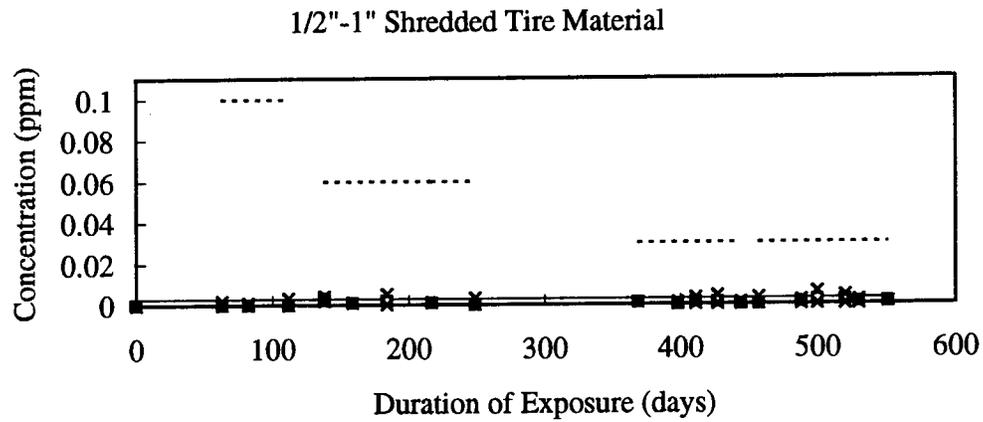
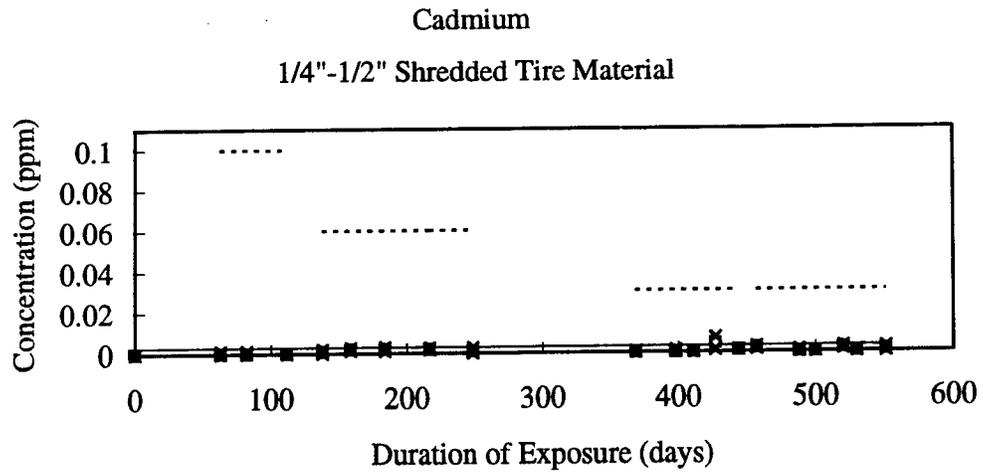


Appendix K-14: The concentration of barium versus duration of exposure for different tire sizes.



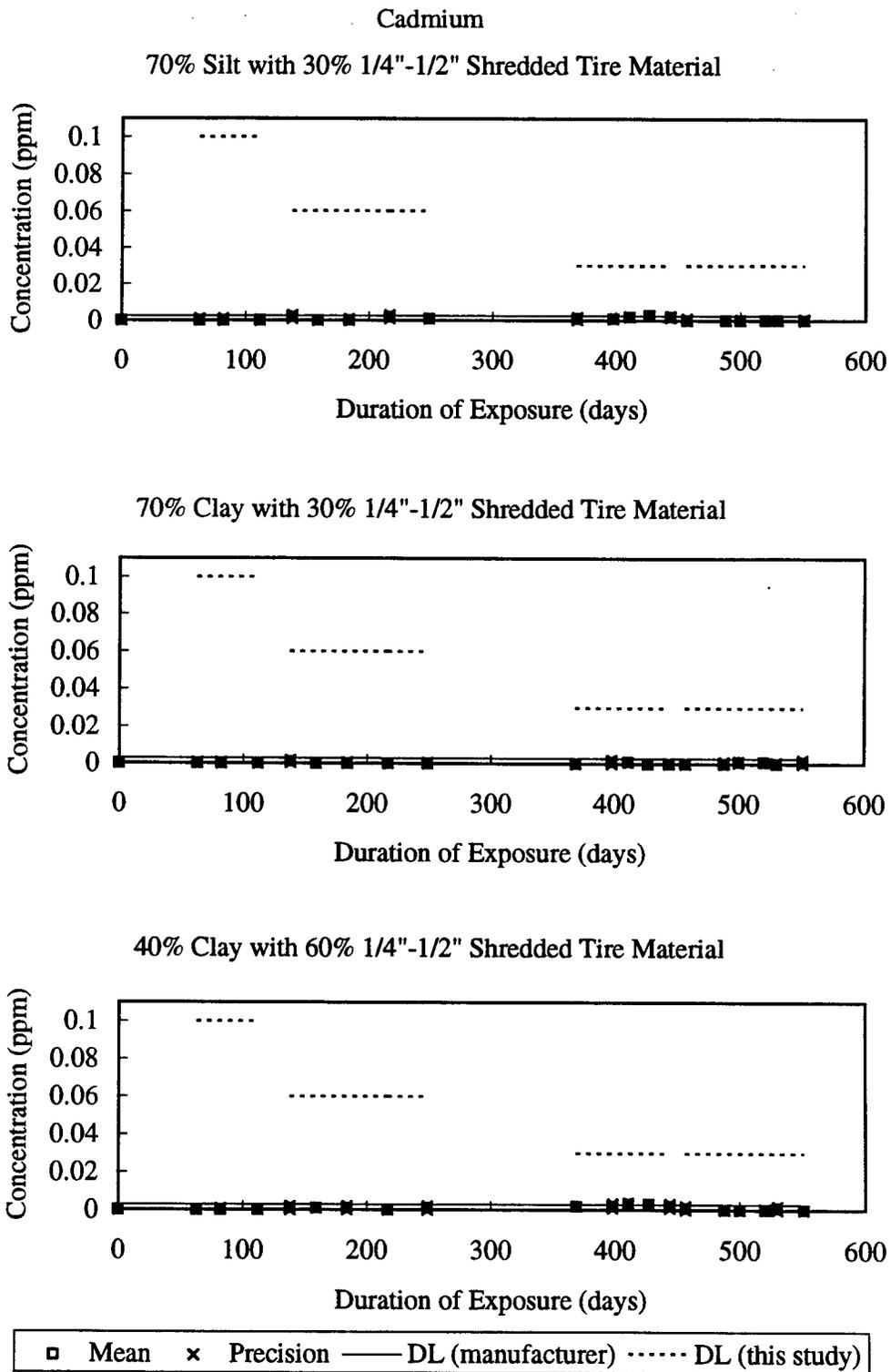
□ Mean × Precision — DL (manufacturer) DL (this study)

Appendix K-15: The concentration of barium versus duration of exposure for soil-tire mixtures.

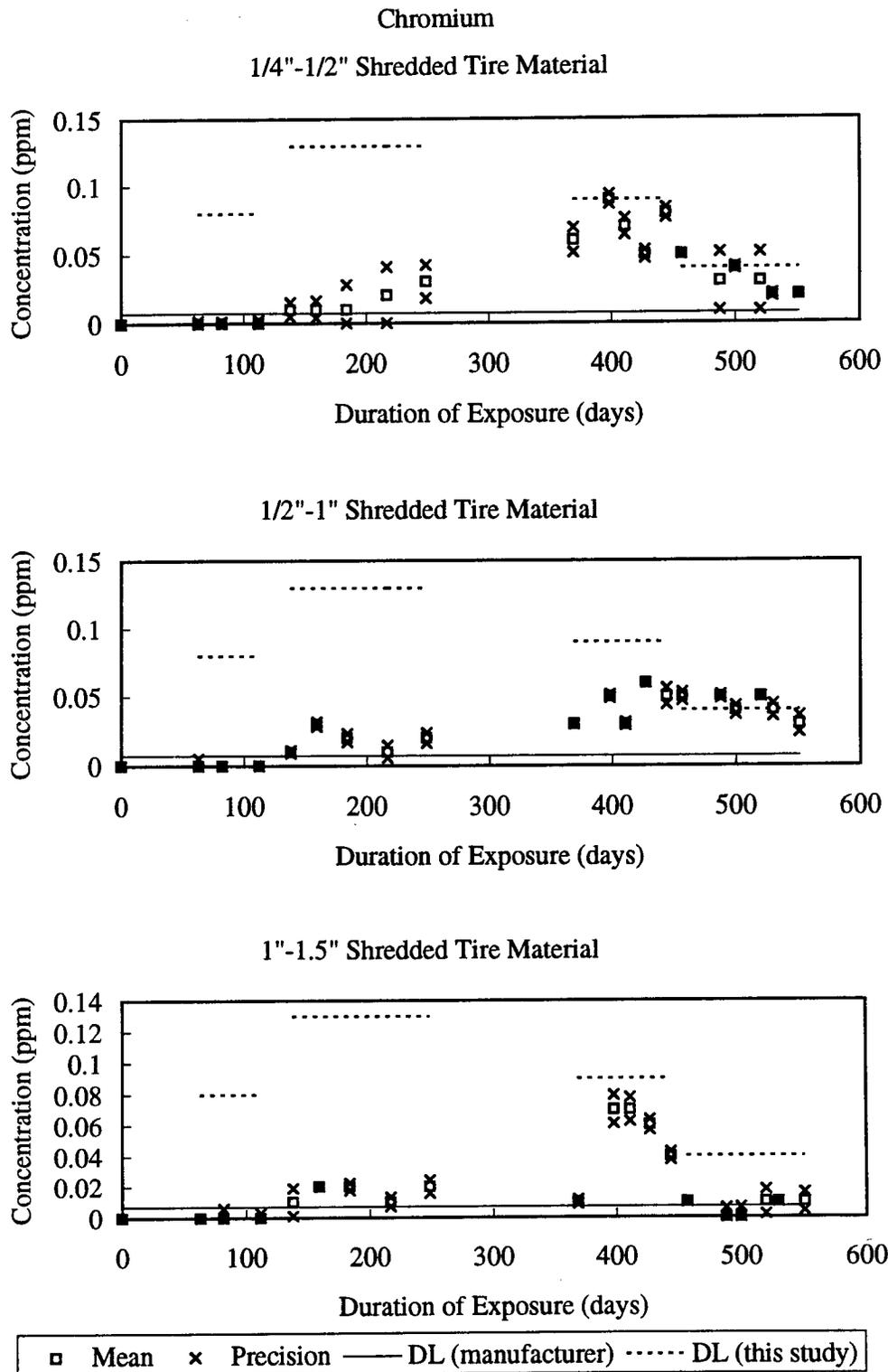


Mean
 Precision
 DL (manufacturer)
 DL (this study)

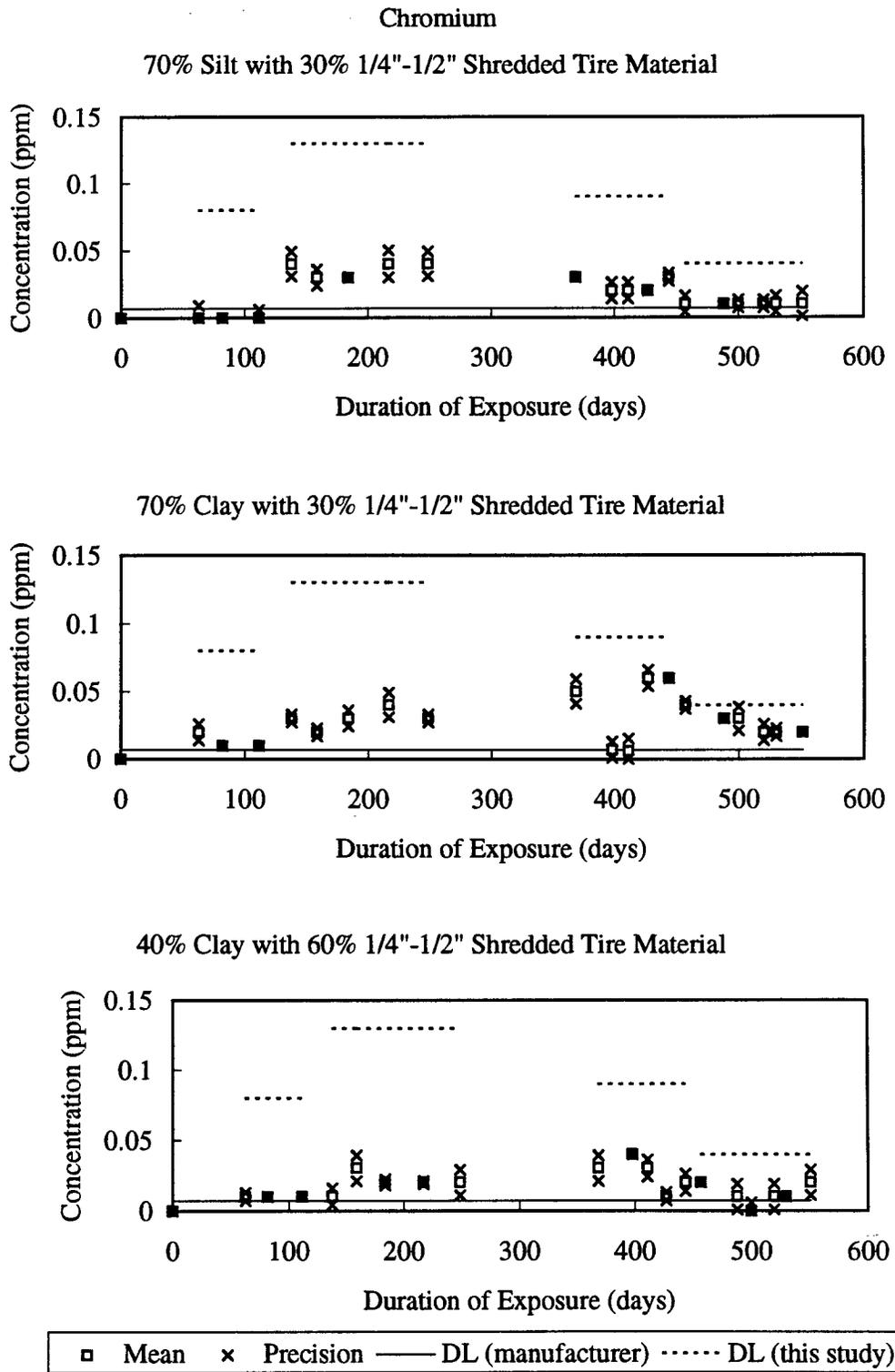
Appendix K-16: The concentration of cadmium versus duration of exposure for different tire sizes.



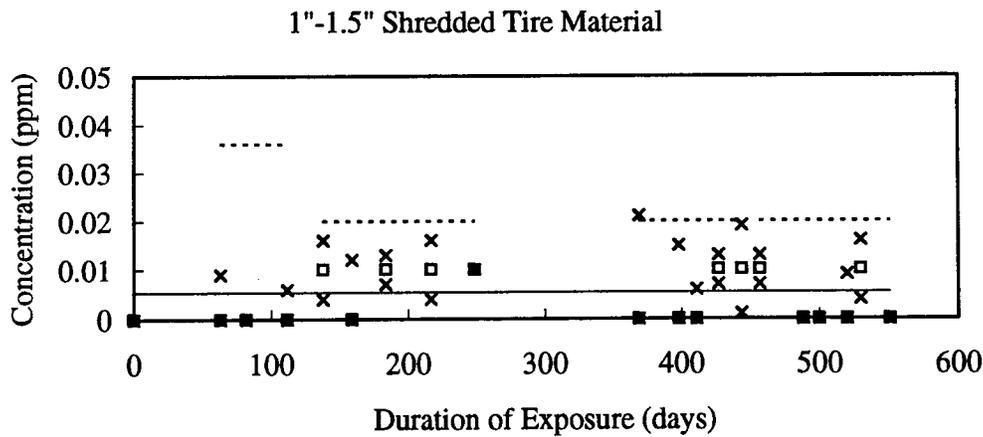
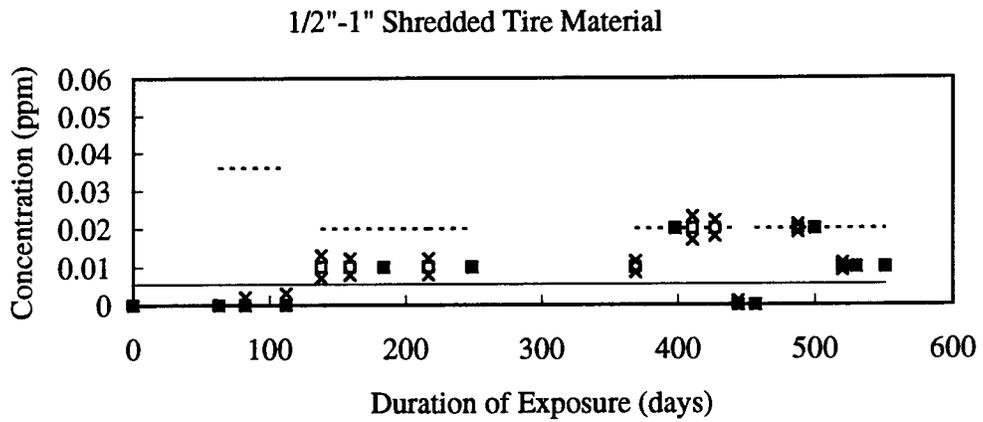
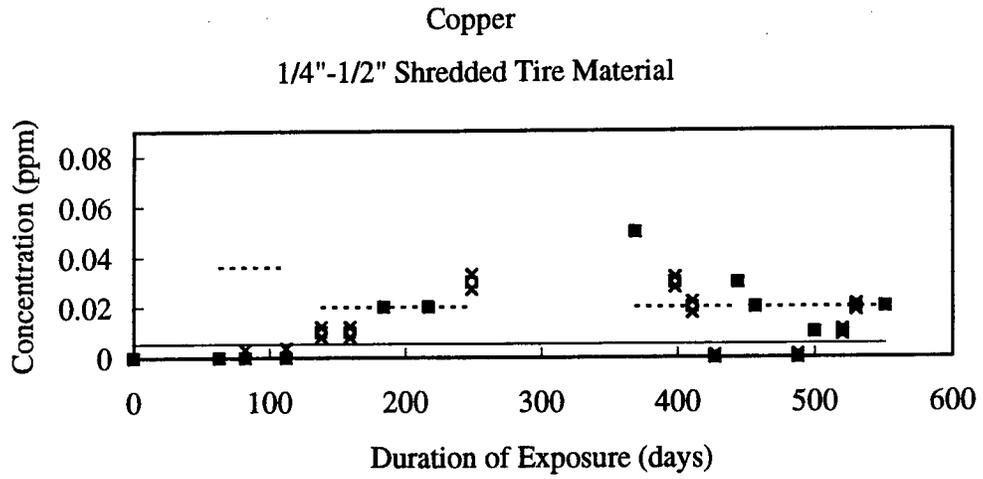
Appendix K-17: The concentration of cadmium versus duration of exposure for soil-tire mixtures.



Appendix K-18: The concentration of chromium versus duration of exposure for different tire sizes.

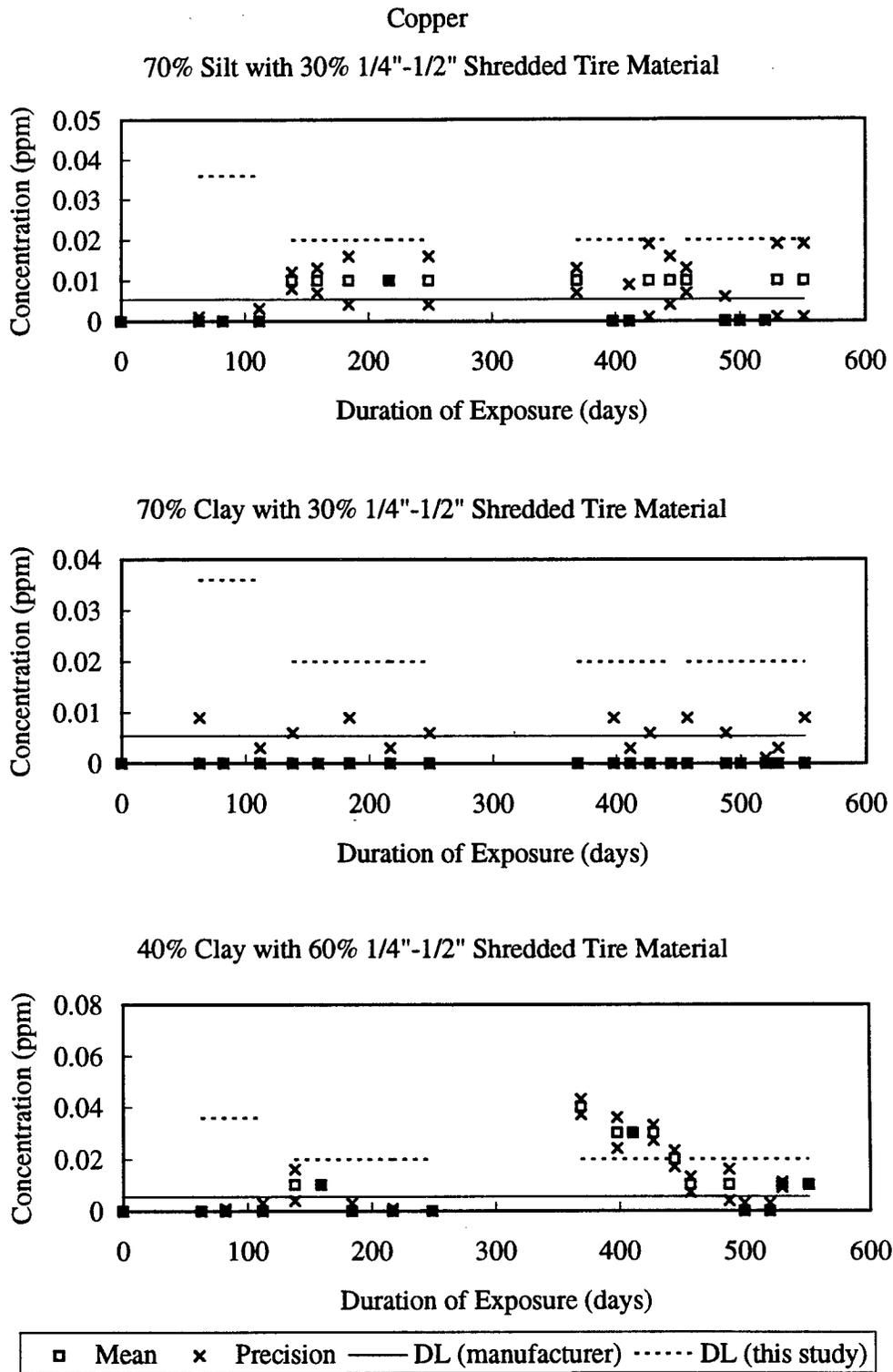


Appendix K-19: The concentration of chromium versus duration of exposure for soil-tire mixtures.

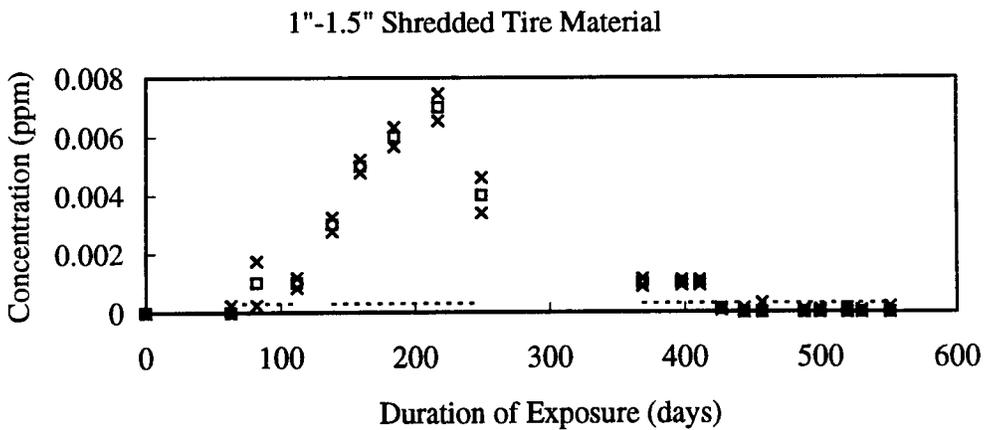
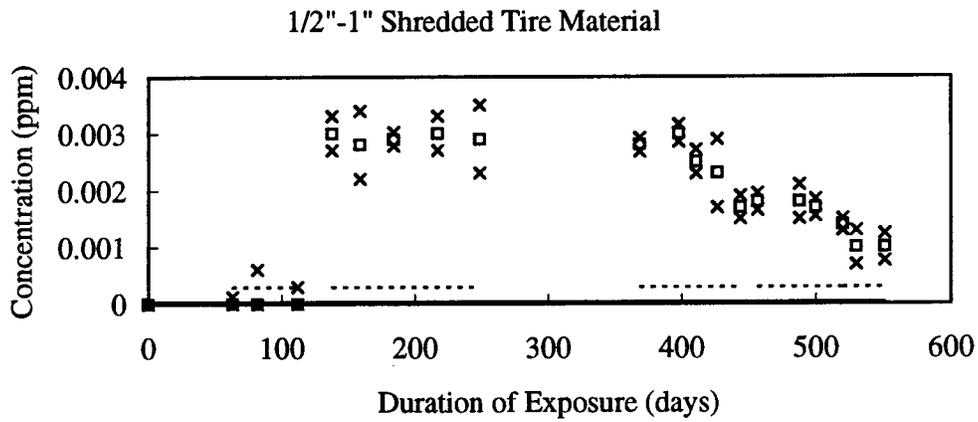
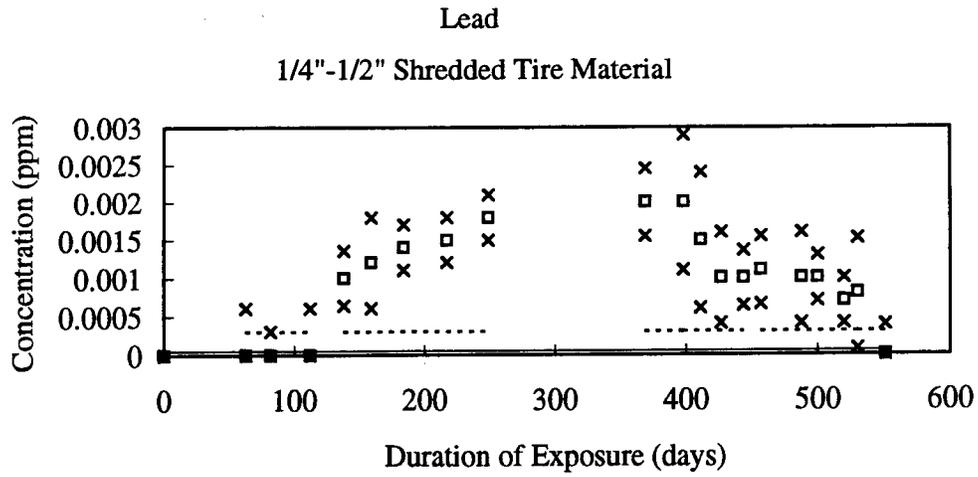


□ Mean × Precision — DL (manufacturer) DL (this study)

Appendix K-20: The concentration of copper versus duration of exposure for different tire sizes.

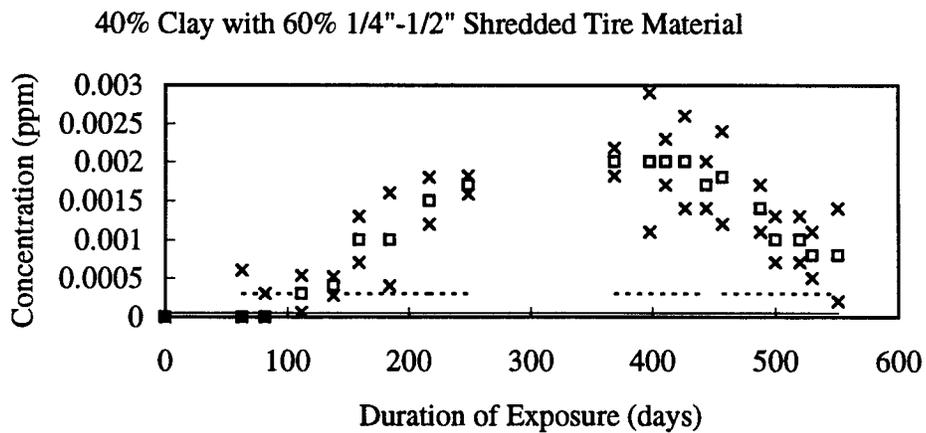
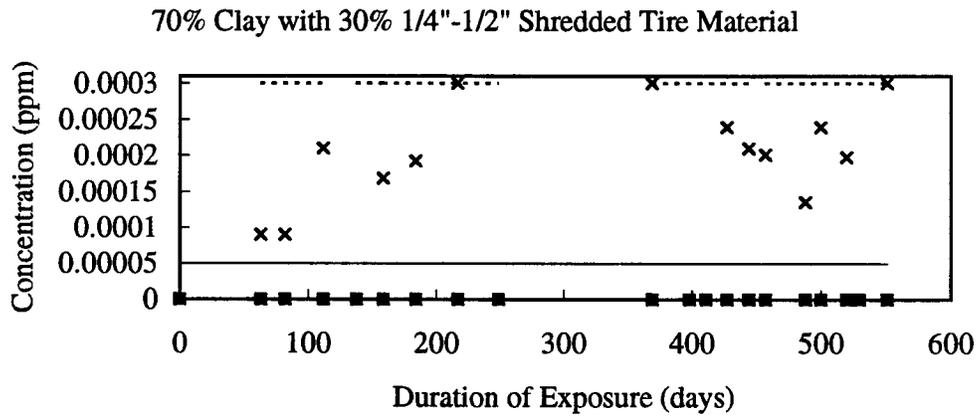
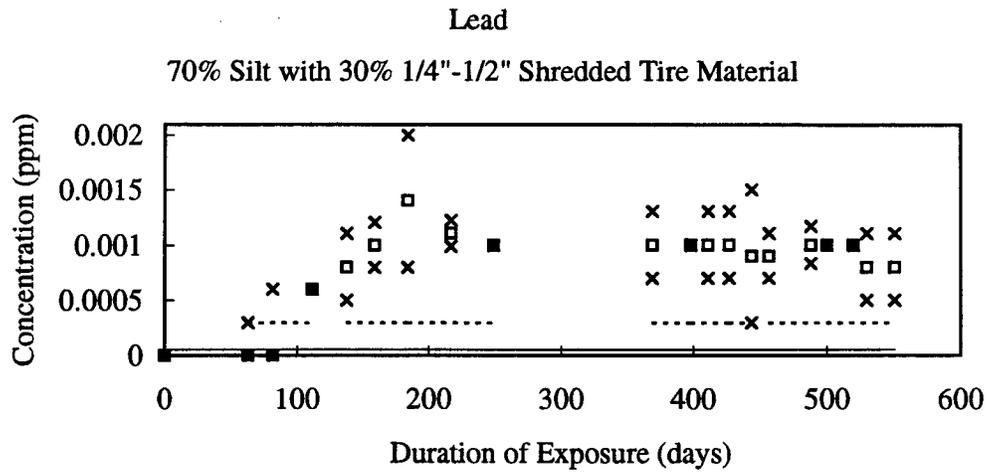


Appendix K-21: The concentration of copper versus duration of exposure for soil-tire mixtures.



□ Mean × Precision — DL (manufacturer) DL(this study)

Appendix K-22: The concentration of lead versus duration of exposure for different tire sizes.



□ Mean × Precision — DL (manufacturer) DL (this study)

Appendix K-23: The concentration of lead versus duration of exposure for soil-tire mixtures.

APPENDIX L

RESULTS OF LEACHATE ANALYSIS FOR EMBANKMENT SAMPLES

Table L-1: Detection limit* of the equipment** used for analysis of leachate from the test embankment.

(a) data provided by manufacturer (Instrumentation Laboratory, 1982) used before 11/1/96

Leachate Concentration (ppm)									
Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.023	0.0013	0.0027	0.0060	0.0071	0.0054	0.0046	0.0014	0.00005	0.0018

(b) data provided by manufacturer (Perkin-Elmer, 1985) used after 11/1/96

Leachate Concentration (ppm)									
Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
0.00001	0.00004	0.000003	0.00002	0.00001	0.00002	0.00002	0.00001	0.00005	0.00001

(c) determined by blank sample

Collecting Date	Leachate Concentration (ppm)									
	Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
7/22/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
8/13/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
9/4/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
9/18/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
10/2/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
10/16/96	0.2	0.33	0.03	0.03	0.04	0.02	0.2	0.3	0.0003	0.45
11/1/96	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3
11/16/96	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3
12/7/96	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3
1/30/97	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3
2/24/97	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3
3/22/97	0.09	0.006	0.0006	0.0006	0.0003	0.0001	0.1	0.004	0.0003	0.3

* The detection limit was three times of the standard deviation of concentration of blank sample.

** The elements of aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed using ICP and the element of lead were analyzed using GFAA before 11/1/96. All elements were analyzed using GFAA after 11/1/96.

Table L-2: Precision* of the equipment** used for analysis of leachate from 1' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)									
	Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
7/22/96	0	0.003	0	0	0.001	0	0	0	0.0002	0.21
8/13/96	0.021	0.0021	0.003	0.006	0	0.001	0.21	0.06	0.0003	0.36
9/4/96	0.018	0	0.001	0.003	0	0	0.12	0.3	0.0003	0.3
9/18/96	0.03	0.0027	0	0.006	0.003	0.003	0.3	0	0.0006	0.36
10/2/96	0.018	0.003	0.003	0	0.006	0	0.21	0.9	0.0004	0.6
10/16/96	0.021	0.003	0	0.003	0	0.001	0.24	0	0.0003	0.6
11/1/96	0	0.0007	0.0003	0.0006	0.0006	0.00006	0	0.0048	0.0006	0
11/16/96	0.012	0.0012	0.0006	0	0.0003	0.00008	0.03	0.00096	0	0.3
12/7/96	0.009	0.0001	0.0006	0.0009	0.0003	0.00009	0.24	0	0	0.3
1/30/97	0.012	0.0003	0.0002	0.0006	0.0009	0.00006	0	0.0024	0.0002	0
2/24/97	0.018	0.0002	0.0009	0.0006	0.0006	0.00005	0.03	0.0012	0.0002	0.12
3/22/97	0.006	0.0006	0.0003	0.0012	0.0006	0	0.006	0.0012	0.0003	0.06

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed using ICP and the element of lead were analyzed using GFAA before 11/1/96. All elements were analyzed using GFAA after 11/1/96.

Table L-3: Precision* of the equipment** used for analysis of leachate from 2' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)									
	Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
7/22/96	0.012	0	0.003	0.003	0.003	0.006	0.18	0	0.0006	0.3
8/13/96	0	0.015	0	0.003	0.001	0.003	0.054	0.234	0.0002	0
9/4/96	0.033	0.018	0.002	0	0	0.001	0.09	0.108	0.0004	0.18
9/18/96	0.009	0.024	0.002	0.006	0	0	0.063	0.144	0	0.24
10/2/96	0.006	0.03	0.001	0	0.003	0.001	0.072	0.126	0.0004	0.27
10/16/96	0.012	0.021	0	0	0.003	0	0.09	0.063	0.0003	0.27
11/1/96	0.006	0.0009	0.0002	0.0027	0.0003	0	0.0198	0.0036	0.0001	0.09
11/16/96	0.003	0	0.0009	0	0.0009	0.0009	0.09	0.0012	0.0001	0.045
12/7/96	0.009	0.0001	0.0003	0.0004	0.0012	0.00025	0	0	0.0003	0.18
1/30/97	0.006	0.0003	0.0018	0.0009	0.0003	0	0.072	0.0036	0.0005	0.09
2/24/97	0.012	0.0003	0.0036	0.0009	0.0003	0.00056	0.054	0.0018	0.0009	0.09
3/22/97	0.009	0.0001	0.0027	0.0004	0.0001	0.00018	0.054	0.0032	0.0001	0.18

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed using ICP and the element of lead were analyzed using GFAA before 11/1/96. All elements were analyzed using GFAA after 11/1/96.

Table L-4: Precision* of the equipment** used for analysis of leachate from 3' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)									
	Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
2/24/97	0.018	0	0.0001	0	0.0001	0.00006	0.03	0.0024	0.00003	0.06

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed using ICP and the element of lead were analyzed using GFAA before 11/1/96. All elements were analyzed using GFAA after 11/1/96.

Table L-5: Precision* of the equipment** used for analysis of leachate from 4' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)									
	Al	Ba	Cd	Co	Cr	Cu	Fe	Mn	Pb	Zn
2/24/97	0	0.0001	0.0001	0.00003	0.0001	0.00009	0.03	0.0036	0.0001	0.03

* The precision was three times of the standard deviation of concentration of leachate sample.

** The elements of aluminum, barium, cadmium, chromium, cobalt, copper, manganese, iron, and zinc were analyzed using ICP and the element of lead were analyzed using GFAA before 11/1/96. All elements were analyzed using GFAA after 11/1/96.

Table L-6: Chemical composition of the leachate from 1' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)										Temp.	pH
	Al*	Ba	Cd	Co	Cr	Cu	Fe*	Mn*	Pb	Zn*		
7/22/96	0	0	0	0	0.001	0	0	0	0	1.13	28	7.0
8/13/96	0.10	0.014	0	0	0.001	0	1.62	0.30	0	1.80	24	6.9
9/4/96	0.16	0.022	0	0.001	0.002	0	2.31	0.40	0	2.40	19	7.1
9/18/96	0.26	0.022	0.0001	0.001	0.004	0	2.70	0.90	0	2.80	20	6.7
10/2/96	0.19	0.030	0.0001	0.001	0.003	0	3.16	1.64	0	3.08	15	6.8
10/16/96	0.27	0.036	0	0	0.003	0	3.27	2.34	0	3.26	16	6.8
11/1/96	0.31	0.040	0.0001	0.002	0.004	0	3.45	0.22	0	4.60	10	7.0
11/16/96	0.29	0.052	0.0001	0.001	0.005	0	4.10	0.31	0	5.00	8	6.9
12/7/96	0.37	0.060	0	0.001	0.005	0	4.20	0.34	0	5.10	8	6.7
1/30/97	0.32	0.070	0.0001	0.005	0.006	0	4.40	0.42	0	5.60	5	6.7
2/24/97	0.27	0.056	0.0001	0.002	0.004	0	4.10	0.51	0	5.50	6	6.7
3/22/97	0.30	0.044	0.0001	0.001	0.003	0	4.20	0.58	0	5.70	10	6.8

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100 for Al, Fe, and Zn and a factor of 4 for Mn after 11/1/96.

 Insignificant data because the concentration is below the detection limit.

Table L-7: Chemical composition of the leachate from 2' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)										Temp.	pH
	Al*	Ba	Cd	Co	Cr	Cu	Fe*	Mn*	Pb	Zn*		
7/22/96	0	0	0	0	0	0	1.26	0	0	1.02	28	7.0
8/13/96	0.09	0	0	0	0	0	2.23	0	0	1.10	24	6.9
9/4/96	0.11	0.005	0	0	0.001	0	2.57	0.80	0	1.60	19	6.9
9/18/96	0.12	0.006	0	0	0.001	0	2.64	1.10	0	2.10	20	6.9
10/2/96	0.16	0.008	0	0	0.002	0	3.02	1.80	0	2.78	15	7.1
10/16/96	0.18	0.010	0.0001	0.001	0.003	0	3.05	2.13	0.0001	2.85	16	6.8
11/1/96	0.21	0.010	0.0001	0.001	0.004	0	3.20	0.20	0	2.90	10	6.7
11/16/96	0.22	0.010	0.0002	0.001	0.004	0	3.30	0.284	0	3.50	8	6.8
12/7/96	0.26	0.010	0.0001	0.001	0.003	0	3.60	0.360	0	4.00	8	6.9
1/30/97	0.30	0.010	0.0001	0.003	0.003	0	3.80	0.384	0	4.00	5	7.0
2/24/97	0.30	0.010	0.0001	0.001	0.004	0	3.80	0.528	0	4.20	6	6.8
3/22/97	0.22	0.010	0.0001	0.001	0.003	0	4.00	0.516	0	4.20	10	6.9

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100 for Al, Fe, and Zn and a factor of 4 for Mn after 11/1/96.

 Insignificant data because the concentration is below the detection limit.

Table L-8: Chemical composition of the leachate from 3' depth of the test embankment.

Collecting Date	Leachate Concentration (ppm)										Temp.	pH
	Al*	Ba	Cd	Co	Cr	Cu	Fe*	Mn*	Pb	Zn*		
2/24/97	0.01	0.002	0	0	0	0	3.9	0.44	0	3.9	6	6.7

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100 for Al, Fe, and Zn and a factor of 4 for Mn.

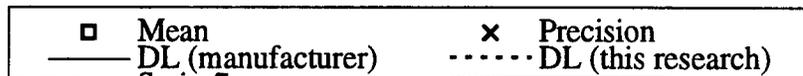
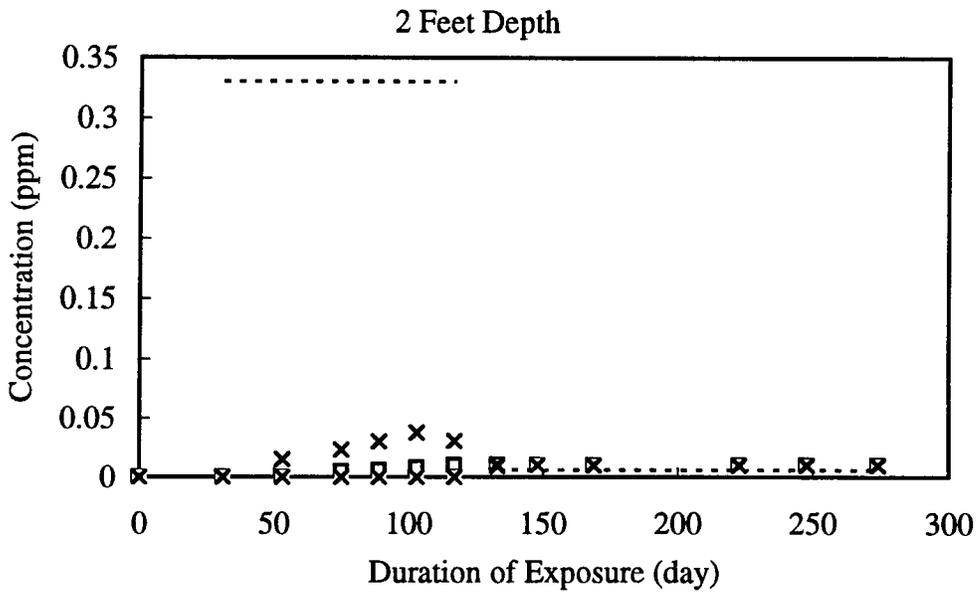
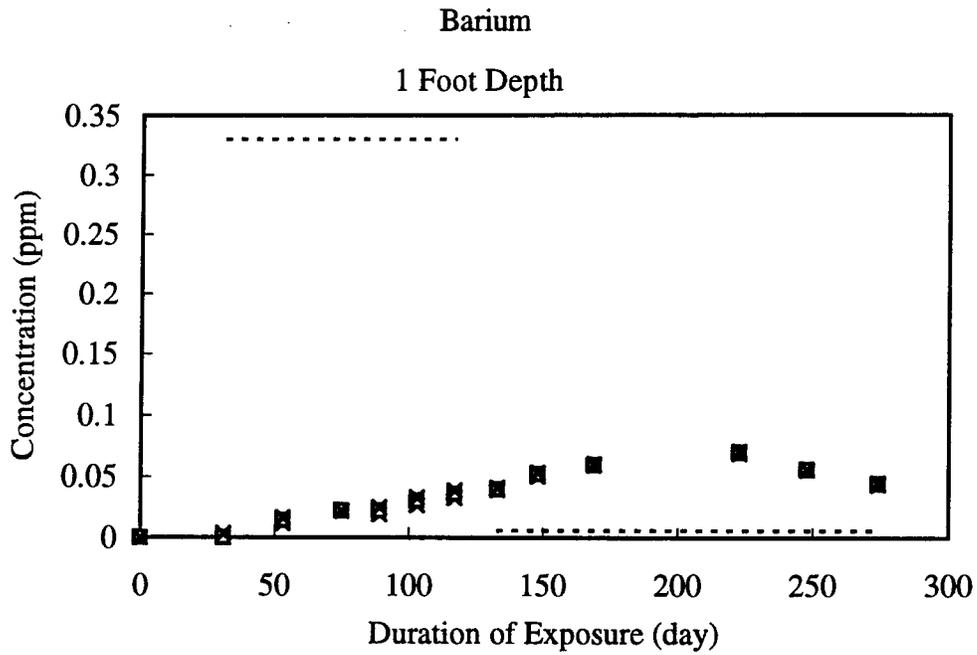
 Insignificant data because the concentration is below the detection limit.

Table L-9: Chemical composition of the leachate from 4' depth of the test embankment.

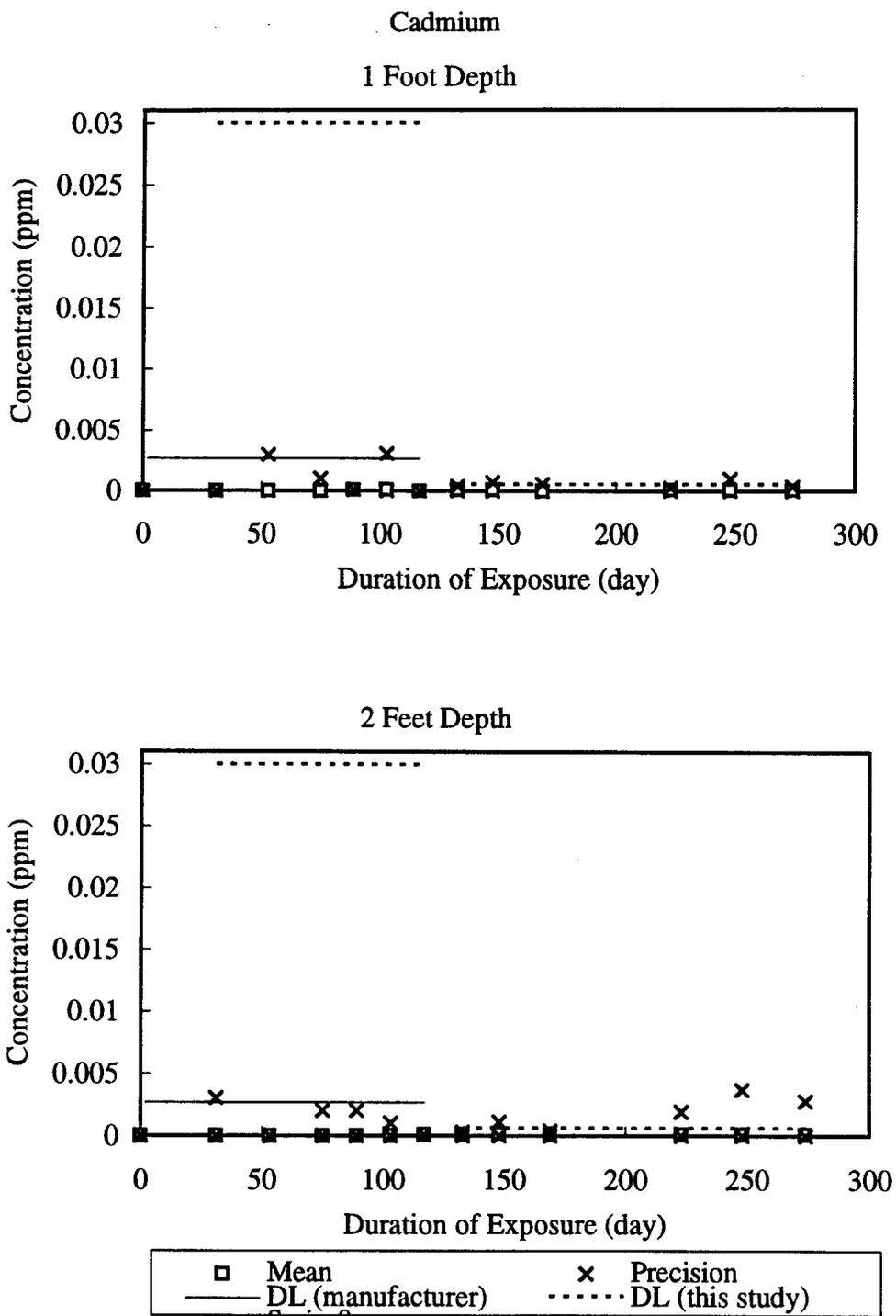
Collecting Date	Leachate Concentration (ppm)										Temp.	pH
	Al*	Ba	Cd	Co	Cr	Cu	Fe*	Mn*	Pb	Zn*		
2/24/97	0	0.002	0	0	0	0	3.1	0.4	0	3.8	6	6.7

* ppm in actual sample; actual solution analyzed was diluted by a factor of 100 for Al, Fe, and Zn and a factor of 4 for Mn.

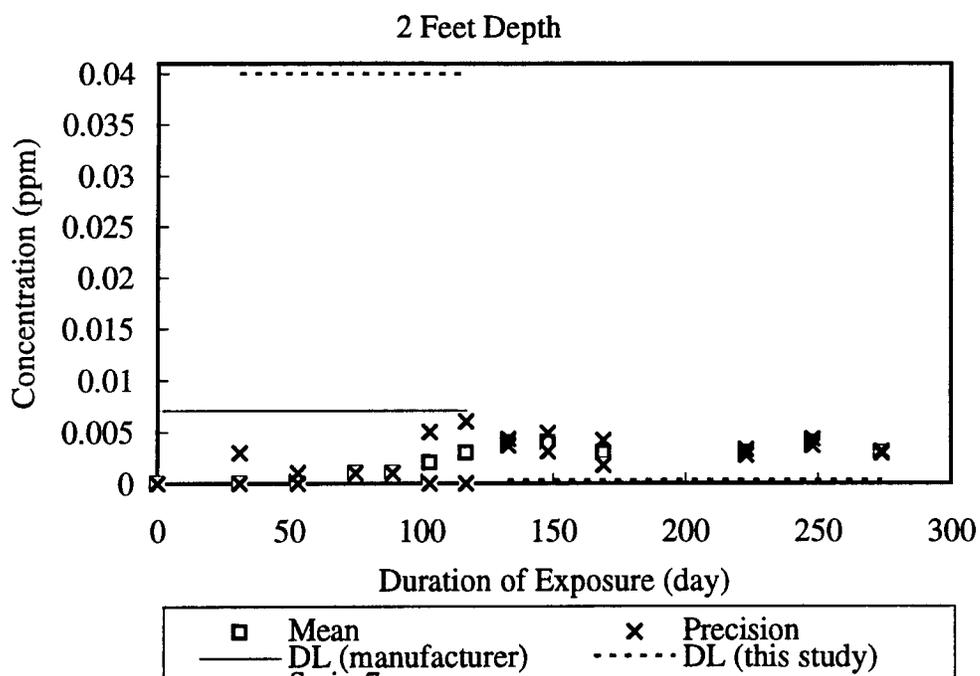
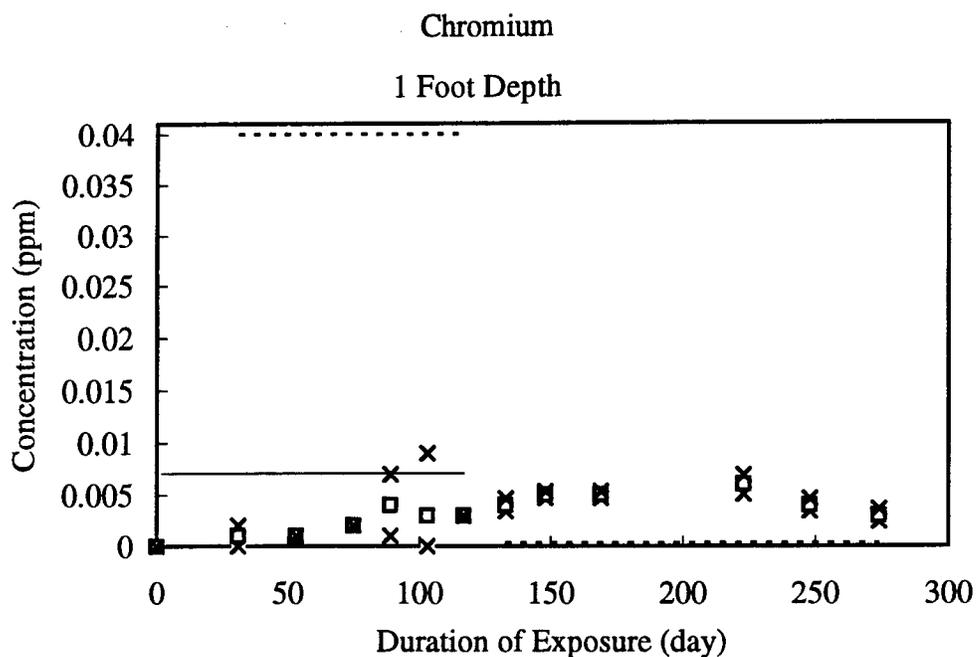
 Insignificant data because the concentration is below the detection limit.



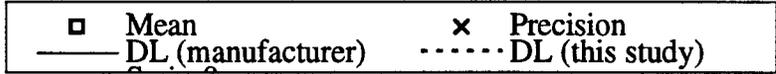
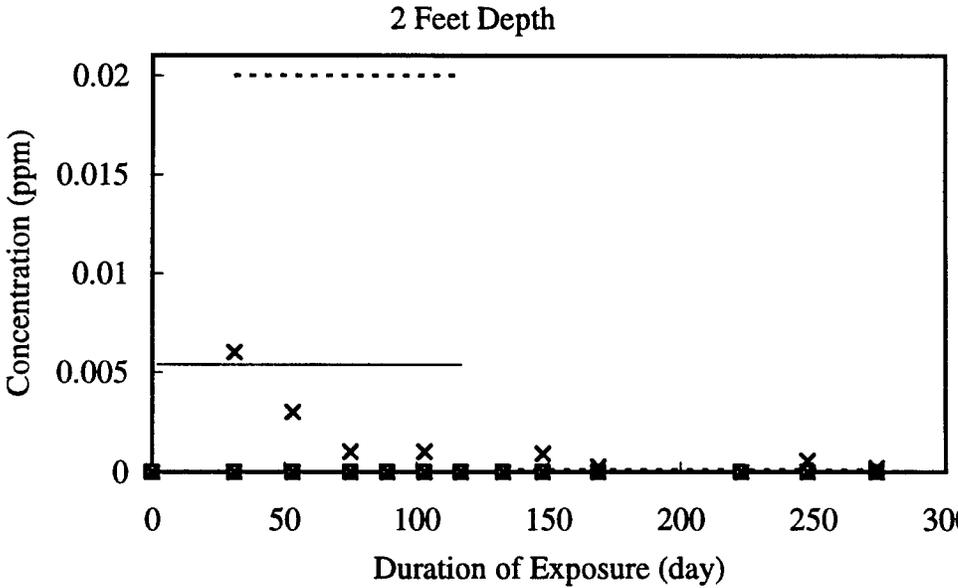
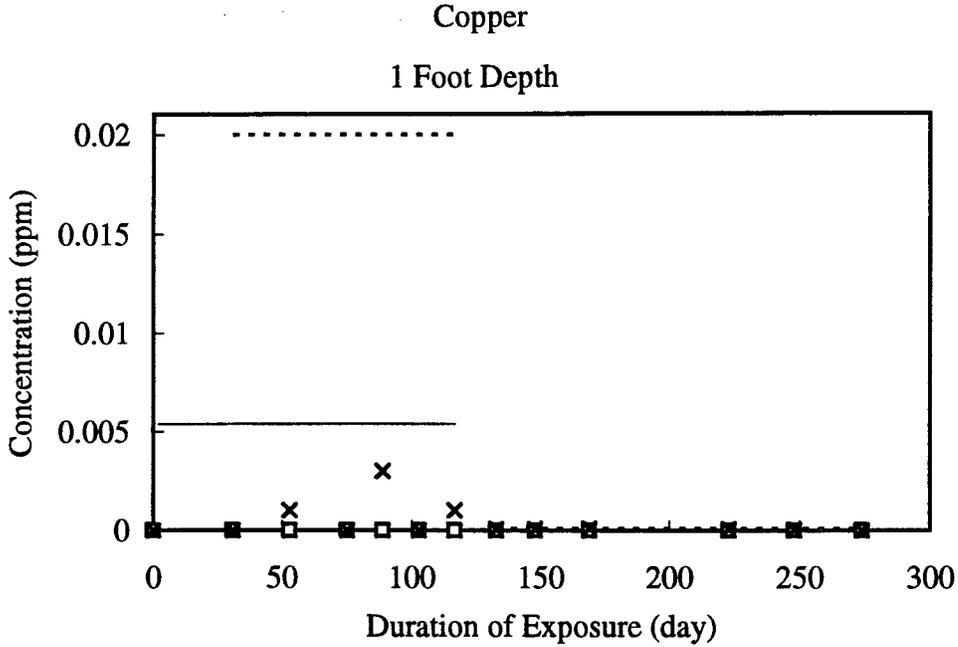
Appendix L-10: The concentration of barium versus duration for different depths in test embankment.



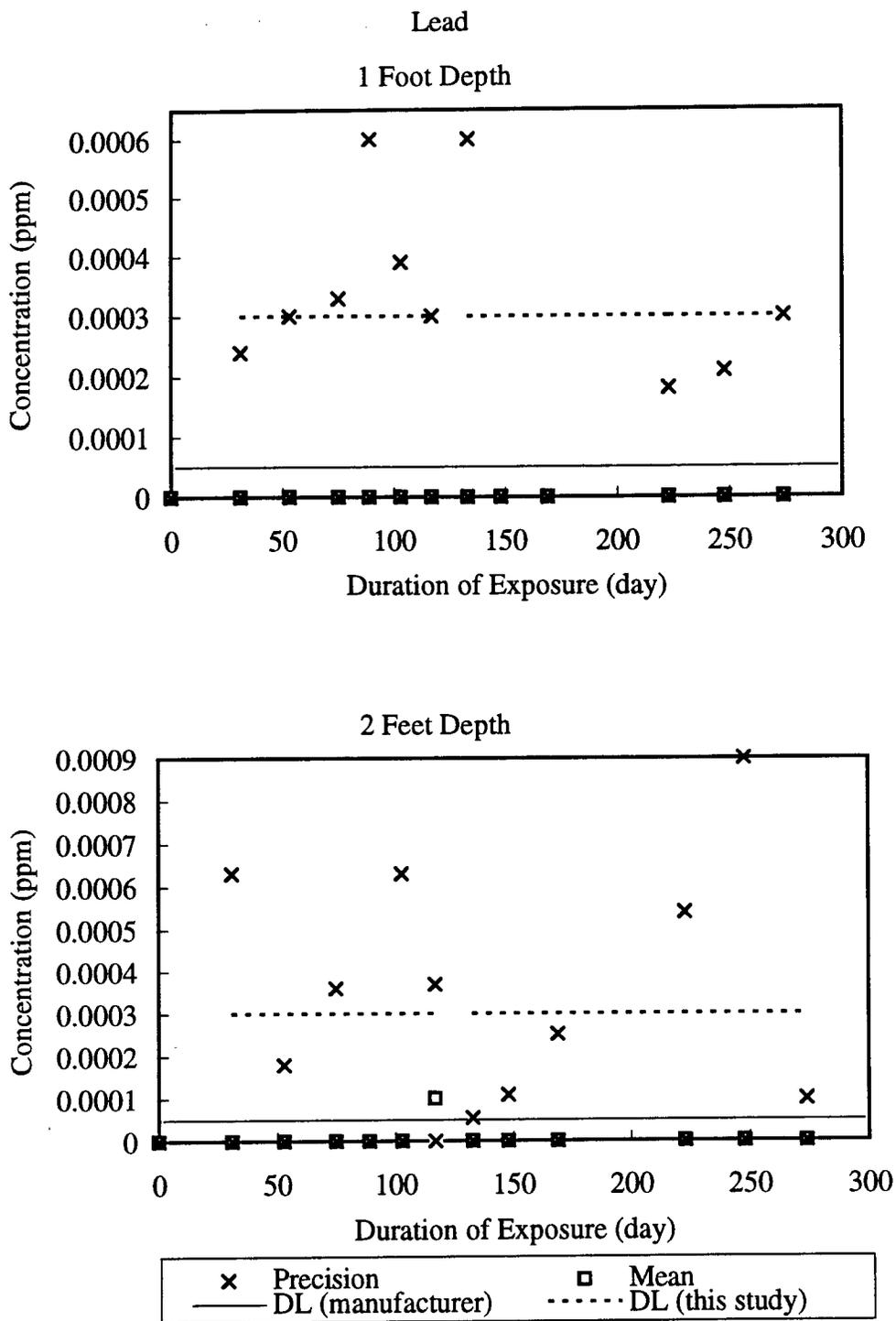
Appendix L-11: The concentration of cadmium versus duration for different depths in test embankment.



Appendix L-12: The concentration of chromium versus duration for different depths in test embankment.



Appendix L-13: The concentration of copper versus duration for different depths in test embankment.



Appendix L-14: The concentration of lead versus duration for different depths in test embankment.

