PERFORMANCE OF A ROAD BASE CONSTRUCTED WITH SHREDDED RUBBER TIRES

by

Riaz Ahmed

A Thesis Submitted to Faculty of Graduate Studies
In Partial Fulfillment of the Requirements of the Degree of

MASTER OF SCIENCE

Department of Civil Engineering
University of Manitoba
Winnipeg, Manitoba

0-612-76741-8

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

*****

COPYRIGHT PERMISSION PAGE

PERFORMANCE OF A ROAD BASE CONSTRUCTED WITH SHREDDED RUBBER TIRES

BY

RIAZ AHMED

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements of the degree

of

Master of Science

ABSTRACT

Currently there are 600 – 850 million scrap tires in North America and 270 million scrap tires are added to the stockpiles annually. These scrap tires in the stockpiles are serious fire hazard, public health hazard and an ugly scar on the landscape. The impacts of environmental constraints compelled researchers to seek innovative use of scrap tires in civil engineering applications, especially in road embankment construction. Civil engineering applications of scrap tires benefit from their lightweight and thermal insulation properties and hydraulic conductivity. Therefore 55 percent of the scrap tires are reused mostly as a tire derived fuel, crumb rubber, backfill material for bridge abutments and retaining walls and in the construction of road embankments. Still 45 percent of the scrap tires are disposed as a landfill, stockpiles and illegal dumps.

The construction of road embankments, using tire shreds as a lightweight fill, can consume a huge quantity of scrap tires. Lightweight fill is used to replace granular fill on a weak subgrade and is of particular interest to highway construction, which provides a means of disposing the tires, and helps reduce the instability of construction over soft and frost susceptible soils. In this case the benefit of the tire shreds is the reduction in overburden stress on the soft subgrade, thereby reducing the settlement.

Until recently, most research has focused on using 150 mm or smaller shreds as a lightweight fill in highway construction. Large size tire shreds have distinct advantages over small size tire shreds such as the lower unit weight and production costs. There is a lack of technical data on the use of large size shredded rubber tires. Given this lack of technical data, a research project was initiated at the University of Manitoba to monitor the performance of a gravel road constructed with shredded tires and produce design guidelines for the suitability of shredded tires as a road base material. The project examined thermal behaviour, ground water quality and mechanical behaviour of large size tire shreds by conducting a field monitoring program and laboratory and field compressibility testing.

The project involved the construction of a gravel road on a very soft subgrade near Winnipeg, Manitoba. The 300-m long road provided access to a gravel pit. The design incorporated 1500-mm thick base layer made of shredded scrap tires. An estimated 300,000-passenger car tire equivalents were used in this section or almost one third of the annual supply of scrap tires in the province of Manitoba.

An extensive field temperature monitoring program was undertaken which included installing thermocouple probes up to a depth of 3m and a data acquisition system to permit year-round temperature monitoring. The thermal behaviour of the tire shreds, established by this in-site automated temperature measurement, has shown the thermal coefficient of the tires to be 0.2832 W/m·°C. The compressibility of the tire layer was monitored in the field and compressibility testing was performed in the laboratory. Three sizes of the tire shreds minus 300 mm, minus 150 mm and minus 50 mm were examined. The elastic modulus of the shredded tires is determined as a function of the bulk density of tires. New model and indices are developed to predict the compressibility of the tire-shred embankment based on the laboratory testing. The effect of tire shreds on the ground water quality is determined based on organic and inorganic water quality testing.

ACKNOWLEDGEMENTS

I would like to express my sincerest gratitude to my advisor Dr. Ahmed Shalaby for his excellent guidance and his time to impart his wisdom. His continuous support and encouragement throughout my Masters degree stimulated my academic and professional interest in the field of Transportation Engineering. I am especially grateful to him for the freedom he gave me in exploring the subject area. I must also give thanks to Dr. Morolo C. Alfaro for his technical knowledge and encouragement in my academic pursuits.

I would like to take this opportunity to express my gratitude to the Manitoba Tire Stewardship Board for providing financial support for the research.

There were many individuals and graduate students who provided help during the field monitoring program and laboratory testing. I wish to thank Mr. Scott Sparrow and Mr. Moray McVey, civil engineering technologists, at the University of Manitoba for their time and patience. I would also like to thank Mr. Scott Murison and Mr. Allan Reggin, civil engineering graduate students, for their participation in the research project.

I would also like to acknowledge my brothers; Rashid Ahmed and Raees Ahmed and my friend Salim Ahmed, back home in Pakistan, for their moral support, not only during my studies, but also throughout my entire life.

This acknowledgement would be incomplete without expressing special thanks to my brother like friend Muhammad Ali Khan. This Masters degree would not have been possible without his help.

DEDICATION

Dedicated to an ever lasting and loving memories of my father
Shahi Bostan

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 General Overview

Waste tires are an ecological and financial burden in many regions of the world. In Canada and the United States, an equivalent of one waste tire per capita is added to the stockpiles annually. Not only are these tire mounds eyesores; they are also environmental and fire hazards. Two environmental and health hazards associated with tire stockpiles are catastrophic fires and insect breeding. The little pools of water retained by whole waste tires create an ideal breeding ground for mosquitoes, which have been shown to spread various dangerous diseases (Engstrom et al, 1993). An Ohio study showed that 80 percent of the children suffering from mosquito vectored disease lived within 100 yards of a tire dump (Liu et al, 1998).

Waste tires are serious fire hazards. The tire fires pollute the air with large quantities of smoke, hydrocarbons and residue such as the Hagersville tire fire in Ontario (Eyles et al, 1990) and the Rosser tire fire in Manitoba (Winnipeg Sun, 2001). Tire fires are also virtually impossible to extinguish once started. For example, the Rhinehart tire fire in Winchester, Virginia, burned for nearly nine months, releasing large quantities of potentially harmful compounds. The tire pile fires are dangerous and highly polluting and the clean up afterwards is very expensive. For example, 3.3 million US dollars were spent in the clean up for the mid-1980's fire in Everett, Washington (Liu et al, 1998). In addition to the two major aforementioned concerns, scrap tires piles also decrease landfill life, as they are non-biodegradable and bulky. Discarded tires, whether scattered or piled up, do not have an agreeable appearance.

These impacts of environmental constraints compelled researchers to seek innovative uses of scrap tires. The major markets for scrap tires are Tire Derived Fuel, rubber products and civil engineering applications. Tire Derived Fuel (TDF) is the biggest segment of scrap tire market. In this method waste tires are burned for electric power generation for plants, cement plants, pulp and paper mill boilers, utility boilers, and other industrial boilers as scrap tires have a specific heat ranging from 28,000 KJ/kg to 35,000 KJ/kg (TFHRC, 2000). Rubber products are manufactured from size reduced rubber either as a crumb rubber or ground rubber. Crumb Rubber is recycled rubber that is obtained by mechanical shearing or grinding tires into small particle sizes less than 6.3 mm (1/4"). Ground rubber is a substitute for a small portion of the fine aggregate (usually 1 to 3 percent by weight of the total aggregate in the mix) used in hot mix asphalt concrete. Crumb rubber is used to increase the viscosity of the asphalt binder in hot mix asphalt paving and in seal coat applications. Ground rubber is used as a fine aggregate substitute in asphalt pavements (TFHRC, 2000).

Civil engineering applications of scrap tires benefit from their lightweight and thermal insulation properties, and hydraulic conductivity. Scrap tires are used as whole tires, slit tires (cut into two halves) and shredded or chipped tires (ranging from 50 mm to 300 mm in longest dimension). These recycled tires are used in various areas such as embankment construction, backfill material for retaining walls and bridge abutments, insulation layer to limit depth of frost penetration, drainage layer and leachate collection system. Use of shredded scrap tires as lightweight fill to replace granular fill on a weak subgrade is of particular interest to highway construction which provides a means of disposing the tires and helps reduce the instability of construction over soft and frost susceptible soils. The benefit of the tire shreds is the reduction in overburden stress on the soft subgrade, thereby reducing the settlement. The construction of road embankments with shredded scrap tires can consume huge quantity of scrap tires however there is a shortage of technical data on its use in roads construction.

Given this lack of technical data, a research project was undertaken by the University of Manitoba. This thesis reports the details of the research program.

1.2 Objectives and Scope

The objectives of this research project were to

- Monitor the performance of a gravel road constructed with shredded rubber tires
- Determine thermal and mechanical behaviour of shredded tires
- Produce design guidelines for the suitability of shredded tires as a road base material

This research specifically examines the performance of gravel surfaced large size (300 mm) tire shred embankment and laboratory deflection testing for the three sizes of the shredded rubber tires (50 mm, 150 mm and 300 mm) with steel protruding from their cut edges. Performance of the road embankment has been evaluated in the winter / spring seasons (December 2000-May 2001). The thermal behaviour of tire shreds is compared with natural ground (clay) since no control section of conventional road has been constructed because of the topography of site and economic constraints. Surface field deflection of the tire-shred embankment has been computed using stationary 21,000-kg dual-tandem axle load. One-dimensional constrained compression deflection tests have been performed based on the material isotropy of the tire shreds using a large size, 900-mm, steel container. A non-linear elastic isotropic deflection prediction model has been developed based on the laboratory compressibility testing of shredded rubber tires, taking into account the actual compaction stress exerted by the construction machinery in the field. Compressibility coefficients for three sizes of shredded rubber tires have been developed and deflection of the tire shreds is predicted using conventional soil mechanics settlement equation. The effects of tire shreds on the shallow ground water quality have been determined by taking samples from the surface water table.

1.3 Organisation of Thesis

To familiarize the reader with the project, the thesis has been organized as follows:

Chapter 2: *Literature Review*

This chapter reviews the literature required to understand the work presented in this thesis. The review summarizes the shredded tire materials and its use in civil engineering applications. The chapter also serves to illustrate the need and significance of the research conducted.

Chapter 3: *Project Background*

Location of project site, soil investigation and construction sequence of the tire-shred embankment are outlined in this chapter.

Chapter 4: *Automated Temperature Measurement and Ground Water Quality Testing*

Chapter 4 discusses the thermal behaviour of the tire shreds established with in-site automated temperature measurements involving installation of thermocouple probes up to a depth of 3m and a data acquisition system to permit year-round temperature monitoring. The chapter also illustrates the instrumentation and data collection and discusses the thermal properties of the tire shreds. The effect of tire shreds on the underlying ground water quality is presented in Chapter 4, by conducting organic and inorganic water quality testing.

Chapter 5: *Deflection Measurement*

Mechanical behaviour of the tire shreds is presented in Chapter 5. This chapter describes field and laboratory deflection response of the tire shreds to various levels of loads. The chapter outlines the deflection measurement-testing program and the development of a layered elastic-isotropic deflection model and deflection indices to predict the deflection of the tire shred embankment based on the laboratory testing of tire compressibility.

Chapter 6: Conclusions and Recommendations

Chapter 6 presents the conclusions and design guidelines drawn from this research. Recommendations for future research work are also described at the end of the chapter.

References and Appendices are included at the end of the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 General

In North America, about fifty five percent of the scrap tires are reused while forty five percent are disposed mostly in illegal dumps, landfills and in stockpiles (NCHRP, 2001). Scrap tires are mostly reused as tire derived fuel, exported and used in civil engineering applications (Liu et al, 1998). This scrap tire inventory is shown in Fig 2.1.

Scrap tire can be recycled as a whole tire, a slit tire, and a shredded or chipped tire. Tire shreds or tire chips are produced using tire shredders. A tire shredder is a machine with a series of oscillating or reciprocating cutting edges, moving back and forth in opposite directions to create a shearing motion, that effectively cuts or shreds tires as they are fed into the machine, Fig 2.2. The shredding process results in exposure of steel belt fragments along the edges of the tire shreds. The size of the tire shreds primarily depends on the design of shredding machine (Bosscher et al, 1995). Production of tire shreds requires two stages processing of the tires, primary and secondary shredding, to achieve adequate size reduction (NCHRP, 2001). Processing the material through one cycle of shredding produces large size tire shreds (150-300 mm). Smaller size of the tire shreds (50-150 mm) is obtained by reprocessing the large size tire shreds until the desired size is achieved. This secondary shredding results in the production of shreds that are more equidimensional than the large size shreds. The tire shreds obtained after the shredding process are generally curved, irregular shaped and many have sharp, tangled and twisted steel reinforcing fibers protruding from their cut edges, Fig 2.3.

In 1995 three highway projects having tire shreds fill experienced an exothermic reaction. The three projects were SR 100 in Ilwaco, Washington, Falling Springs Road in Garfield County, Washington and a retaining wall project in Glenwood Canyon, Colorado. The three tire shreds highway fills that have experienced ignition problems appear to have had aggravating circumstances namely (Humphrey, 1996).

- Oxidation of exposed steel belts
- Oxidation of rubber
- Microbes consuming liquid petroleum products
- Organic matter leached into tire shreds fill
- Fertilizer washed into tire shreds fill
- Thickness of tire shreds embankments, 7 to 20 m

Minimum overall thickness of tire shred embankments is one of the important factors for spontaneous ignition. Results from a previous investigation indicated hot spots have developed only in shredded tire stockpiles that are more than 4.5 m high and only when the material was composed of 50-mm tire chips (Hager et al. 1998). The two shredded tire fills in Washington, which have experienced detrimental heating reactions were both over 7.6 m thick and were subjected to other aggravating factors. The tire retaining wall in Colorado was 18.3 meter high (Humphrey, 1996).

As a result of these problems, guidelines to minimize internal heating of tire shreds fills were developed by a group consisting of representatives from the Federal Highway Administration (FHWA), academia and the scrap tire industry. These guidelines were issued by the FHWA and subsequently published in ASTM D6270-98 (ASTM, 1998). In developing these guidelines, the insulating effect caused by increasing the fill thickness and the favourable performance of projects with fill thickness less than 4-m have been considered. These design guidelines are less stringent for projects with thinner tire shreds layer.

The guidelines are divided into two classes; Class I are fills with tire shreds layer less than 1-m thick and Class II are fills with tire shreds layers 1-3 m thick. The general design guidelines for all tire shreds fill states that all tires shall be shredded such that the largest shred is 0.6 m in length and at least one sidewall shall be severed from the tire shred. The tire shreds shall be free of all contaminants such as oil, grease, gasoline, diesel fuel, etc., which could create a fire hazard. In no case shall the tire shreds contain the remains of tires that have been subjected to a fire because the heat of a fire may liberate liquid petroleum products from the tire that could create a fire hazard when the shreds are placed in a fill.

Recent tire shreds fill constructed in accordance with new design guidelines, which minimize internal heating, remained inert (Dickson et al. 2000, Wheaten et al. 1997).

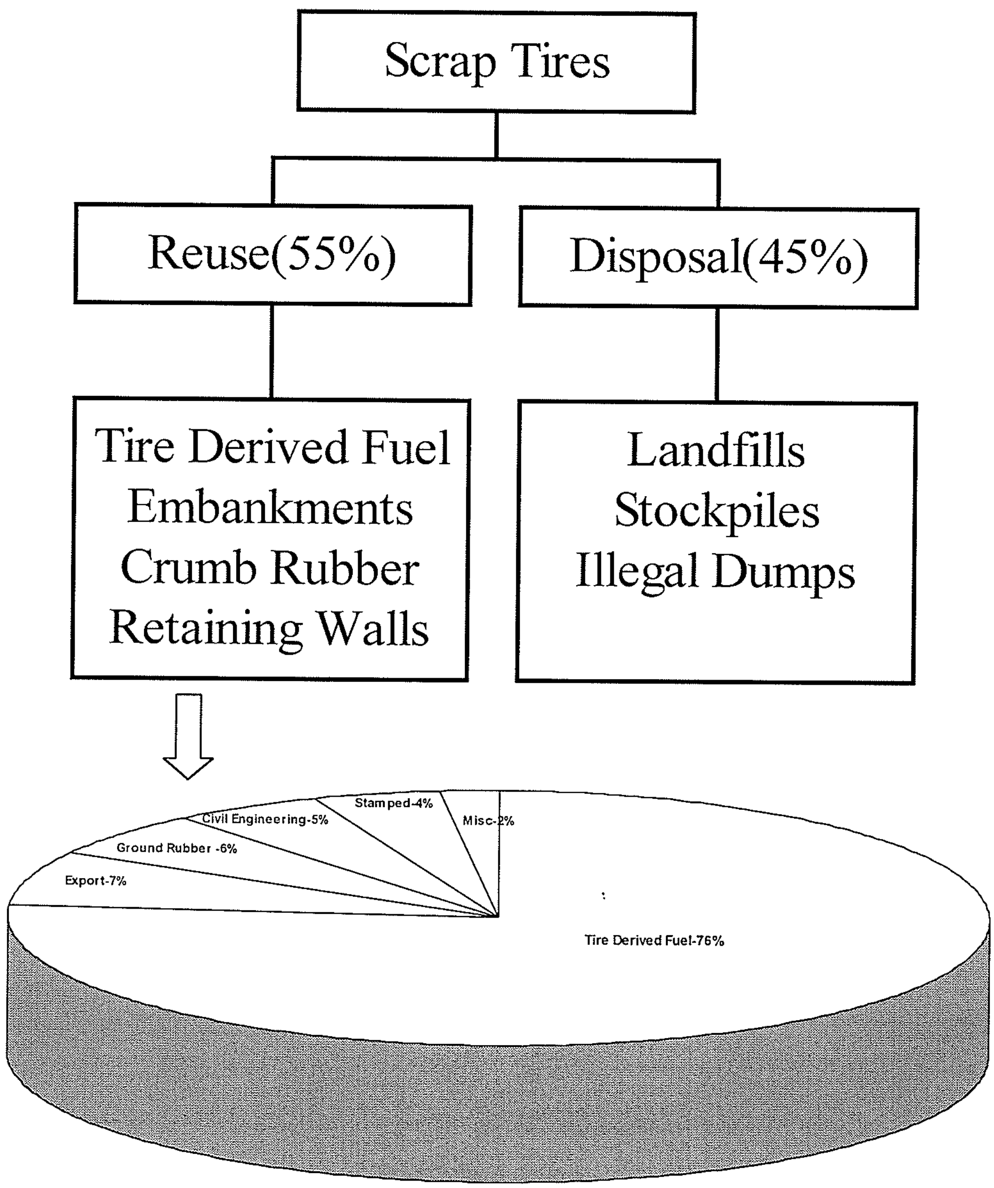


Figure 2.1 Scrap tire inventory

Figure 2.2 Typical shredding process

Figure 2.3 Typical tire shreds obtained from the shredding process

2.2 Composition of Rubber Tires

A typical scrapped passenger car tire weighs 9.1 kg. Approximately 5.4 -5.9 kg consists of recoverable rubber, composed of 35 percent natural rubber and 65 percent of synthetic rubber (TFHRC, 2000). Scrap tires are also the source of the metals shown in Table 2.1, (NCHRP, 2001).

Table 2.1 Metal concentration in scrap tires

Trace Metal	Concentration (mg/kg)	Trace Metal	Concentration (mg/kg)
Aluminium	280	Magnesium	< 500
Barium	< 20	Manganese	28
Beryllium	< 0.5	Molybdenum	1
Boron	< 500	Nickel	3.3
Cadmium	3.6	Selenium	< 5
Cobalt	107	Strontium	< 100
Chromium	3.3	Titanium	48
Copper	30	Vanadium	< 1
Iron	4480	Zinc	15500
Mercury	0.1		

2.3 Engineering Properties

2.3.1 Size

The maximum size of tire shreds depends on the manufacturing process. Tire shreds are essentially flat, irregularly shaped that may or may not contain protruding sharp pieces of steel. The longest dimension of tire shreds indicates the size of the tire shreds. In most cases the size of the tire shreds used in the construction is from 13 to 152 mm (Graham et al, 2001). However larger sizes of the tire shreds from 150-1400 mm have been used in some cases for construction and laboratory testing (Dickson et al, 2001, Graham et al, 2001).

2.3.2 Specific Gravity and Water Absorption Capacity

The specific gravity of the tire shreds is less than half of the typical soil (Humphrey and Sandford, 1993). The typical specific gravity for soil ranges from 2.60-2.80. The water absorption capacity is the amount of water adsorbed onto the surface of the tire shreds. It is expressed as the percent water based on the dry unit weight of the tire shreds. The water absorption capacity of glass belted and steel belted tires are 3.8 and 9.4 percent respectively (Humphrey, 1996).

2.3.3 Unit weight

Tire shreds dumped loosely into a compaction mold have a dry unit weight ranging from 336 kg/m3 to 496 kg/m^3. The compaction energy has a small effect on the compacted dry unit weights of tire shreds and range from 608 kg/m^3 to 688 kg/m^3. For comparison the dry unit weight of tire shreds is 1/3 of typical soil unit weight (Humphrey, 1996).

2.3.4 Compressibility

Compressibility of pure tire shred is seven times higher than dense sand. Edil and Bosscher (1994) demonstrated that mixing 40 percent sand by weight with shredded rubber tires reduced the compressibility by 50 percent. Compression tests by Humphrey and Sandford (1993) using 305 mm diameter and 318 mm high PVC mold showed 42 percent strain for 75 mm maximum size tire shreds at a stress level of 400 kPa. This research indicated that tire chips are highly compressible during first cycle of loading. The subsequent load/unload cycle tends to have a lesser effect on the compressibility of tire chips. A Poisson ratio of 0.30 and an elastic modulus of 100 kPa were calculated. Compressibility tests using 300 x 300 mm mold on 100 mm size tire shreds showed a strain of 44 percent at a vertical pressure of 385 kPa (Hsieh and Wu, 2000).

2.3.5 Shear Strength

The friction angle and the cohesion intercept of the tire chips range from 19° to 25° and 8 to 11 kPa, respectively (Humphrey and Sandford, 1993). The large-size of tire shreds typically used for civil engineering applications requires that specimen sizes be several times greater than that used for common soils (Humphrey, 1996). The tests on large-size tire shreds (40 mm to 1400 mm in length) have shown the friction angle of 37° and cohesion of 3.1 kPa and that the shear strength is independent of the size of tire shreds (Graham et al, 2001), Fig 2.4. Tire shreds have a shear modulus value of 2700 kPa (Han, 1998).

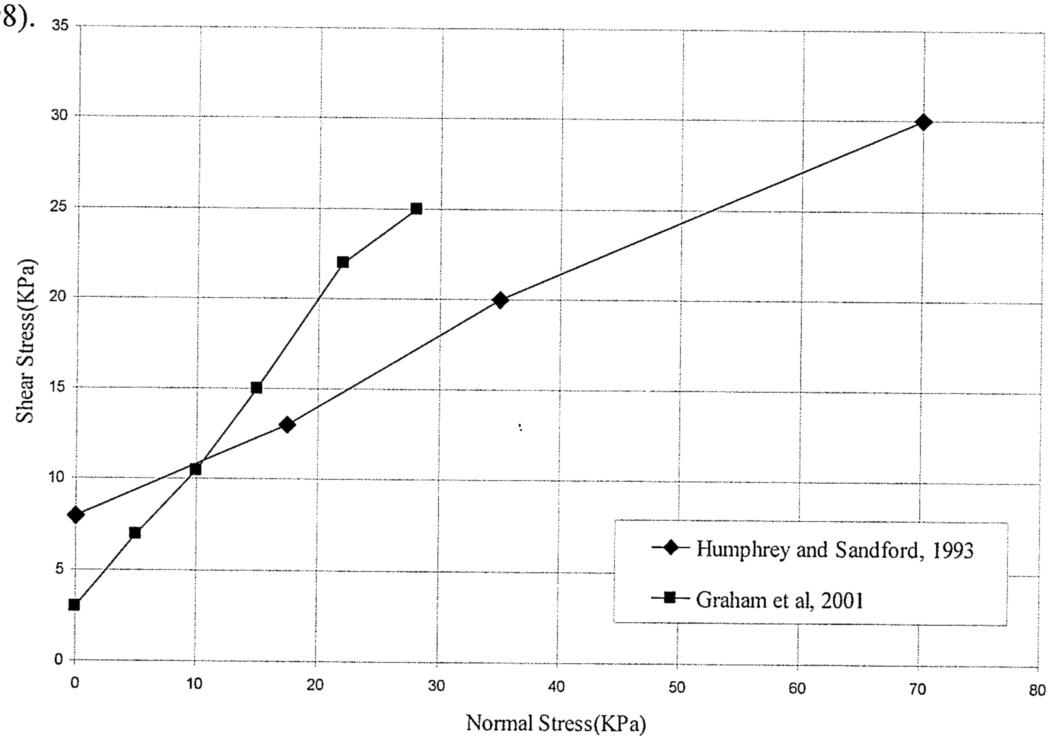


Figure 2.4 Shear strength of shredded rubber tires

2.3.6 Thermal conductivity

The thermal conductivity of tire shreds is significantly lower than for conventional aggregate upto 18 times lower than gravel (Humphrey, 1996). For tire shreds smaller than 25 mm in size, the thermal conductivity can be measured by the Guarded Plate Apparatus while for tire chips larger than 25 mm in size, the thermal conductivity can be measured using a large scale Guarded Plate Apparatus (ASTM, 1998). The apparent thermal conductivity of tire chips varies from 0.20 to 0.32 W/m·°C and there is an overall trend that apparent thermal conductivity increases as density decreases (Humphrey et al, 1997).

2.3.7 Permeability

The Permeability of tire chips smaller than 19 mm can be determined in accordance with ASTM Test Method D 2434. Tire shreds and tire shreds/soil mixtures used in civil engineering applications usually have a majority of their particles larger than 19 mm so permeability can be measured in a larger Permeameter (ASTM, 1998). The permeability of tire chips and tire chips/soil mixtures has been measured with constant head Permeameter and was found to be 7.7 cm/sec for 50-mm tire shreds (Humphrey and Sandford, 1993). Uncompacted tire chips have high permeability of about 1.0 cm/sec. Overburden pressure reduces the void ratio and permeability, a typical value of 0.1 cm/sec can be expected in typical highway applications (Bosscher et al, 1992).

The engineering properties of tire shreds are summarised in Table 2.2.

Table 2. 2 Summary of engineering properties of tire shreds

Engineering property	Approximate value	Remarks
Size (mm)	50-300	
Specific gravity	2.6-2.8	
Water absorption capacity (%)	3.9	Glass belted
	9.4	Steel belted
Unit weight (kg/m^3)	300-500	Uncompacted 25-75 mm size tire shreds
	600-700	Compacted 25-75 mm size tire shreds
Compressibility (%)	40	At 400 kPa surcharge
Poisson's ratio	0.30	
Elastic modulus (kPa)	1100	75 mm size tire shreds
Internal friction angle (degree)	19 to 25	
Cohesion intercept (kPa)	8 to 11	
Shear Modulus (kPa)	2700	75 mm size tire shreds
Thermal conductivity (W/m·°C)	0.20 - 0.30	At a density range of 0.58 to 0.79 Mg/ m^3
Permeability (cm/sec)	0.1	Compacted

2.4 Civil Engineering Applications of Tire Shreds

2.4.1 Lightweight Fill Road Embankments

Tire shreds are suitable alternative material for roads construction on a very soft subgrade due to its low unit weight. The construction of roads across soft ground using conventional earth fills presents construction problems. To reduce the weight of the highway structure at such locations, wood chips or sawdust have traditionally been used as a replacement for conventional materials. Wood is biodegradable and lacks durability. Rubber tires are non-biodegradable and are more durable (Ahmed and Lovell, 1992).

The Oregon Department of Transportation used 400,000 shredded tires as a lightweight fill and described the experience as a success (Read et al, 1991). In Minnesota 23 sites have been documented throughout the state, which have used over 80,000 cubic yards of shredded tires as a light weight fill for roads construction (Engstrom, 1994). The University of Wisconsin constructed a test embankment consisting of 10 sections using locally available aggregates and shredded tires in a number of different ways. The embankment was exposed to heavy incoming truck. Field data was collected to assess the stability and deformation of the road surface. It was reported that the tire shreds used as a lightweight fill performs better when covered by 3-ft thick soil cap. The findings supported the use of properly confined tire shreds as a lightweight fills in highway applications (Edil et al, 1992). In Southern Maine, 20,000 tires were used in road section as a lightweight fill beneath roads as a field trial and the section performed well (Humphrey and Nickels, 1994). In Virginia, 1.7 million tires were used in a test embankment. It was concluded that tire shreds is a good lightweight fill alternative for a poor subgrade soils (Hoppe, 1994). Tire chips using 65,000 tires in 2500 lineal feet of local road were used in the base course as alternative lightweight gravel in Vermont (Frascoia, 1994). The tire chips (cost of $ 1 per cubic yard) proved to be an economical option as compared to gravel (cost of $ 3.85 per cubic yard). In Wyoming, 630,000 tires were used as a lightweight fill option for repair of a highway misaligned by a landslide and shredded rubber tires was a good light weight option (Hager et al, 1998). In New York, 2,500 metric tons of tire shreds were used as a core of a prototype tire shred embankment section. The placement and compaction of tire shreds was easily performed with typical construction equipment (Dickson et al, 2001).

2.4.2 Insulating Layer to Limit Frost Penetration

Tire shreds have been used as an insulating layer to limit frost penetration into underlying subgrade soils and in frost heave areas. Reducing frost penetration allows engineers to reduce thickness of the base layer. In Richmond, Maine, a gravel road test section insulated with scrap tires chips was constructed to assess the performance of shredded tires to limit frost penetration. This full-scale trial showed that tire shreds could reduce penetration of freezing temperature into underlying subgrade soil (Eaton et al, 1994).

2.4.3 Retaining Wall and Bridge Abutment Backfill

Tire shreds have economic advantages as a backfill material because of the reduction of lateral pressure on the retaining walls and smaller wall thickness (Lee et al, 1999). University of Maine constructed 5m high retaining wall test facility to investigate the use of tire shreds as a backfill for conventional retaining walls. The average at-rest lateral stress for tire shreds was 45 percent less than expected for conventional granular backfill (Tweedie et al, 1998).

2.4.4 Tire Shreds as Drainage Layer

The tire chips are substitute for granular soils in edge drains, as a drainage layer at bottom of subbase course and in landfill liner or landfill cap, due to its high permeability (Humphrey, 1996).

2.5 Justification for Research

Tire shreds are more flexible and compressible than granular materials. The relatively high compressibility of the tire shreds is a concern in the construction of road embankments and is a challenge to practitioners. Until recently, most research has focused on smaller size of the tire shreds by constructing test embankments and conducting laboratory testing. However there is a lack of design data on large size tire shreds.

A large size tire shred embankment was constructed in this study. To investigate the behaviour of large size tire shreds and to address the resilience of the material for higher stress level, cyclic loading-unloading confined compression tests were performed using 900 mm diameter container. A layered elastic-isotropic deflection model based on one-dimensional constrained compression laboratory tests on three sizes of the tire shreds was developed to predict the deflection of road embankments constructed of three sizes of the tire shreds. The data presented in this thesis can be useful for researchers and practitioners.

CHAPTER 3

PROJECT BACKGROUND

3.1 Description of Project Site

The project site is located 5 Km North-East of Winnipeg, Manitoba, near the intersection of PR 213 and PR 207. A new road is to provide access to an active gravel pit. The topography of the site is flat to undulating. During the spring melt; the topography leads to poor drainage and areas of standing water. The site is mostly a swampy area with an influx of surface water flowing from an adjacent golf course.

3.2 Soil Investigation

A good understanding of the soil characteristics is necessary to evaluate the performance of the road. A soil investigation was carried out to assess the subsoil conditions of the site (Klymchuk et al, 1999). Four boreholes were hand augured with a 50 mm diameter bit to depths of 2.4 m and 3.0 m. The boreholes were drilled from the existing ground surface. A borehole was drilled every 60 m over a length of 183 m. Due to partial construction of the road; boreholes 1 and 2 were drilled in the ditch beside the road. Boreholes 3 and 4 were drilled on the centreline of the proposed road. Samples were obtained directly off the auger for laboratory testing. A plan view of the borehole locations is shown in Figure 3.1.

The samples were brought to the University of Manitoba Geotechnical Laboratories for soil testing. The tests performed in this soil investigation included the natural moisture content, grain size analysis, Atterberg limits, soil classification, and direct shear test. The natural moisture content was measured for each sample taken at each borehole. The grain size analysis, Atterberg limits, and soil classification, were completed using mixtures of soil samples. The mixtures combined similar samples taken from different boreholes to determine representative properties of the soils at this site. Each mixture consisted of similar soils in colour, texture, and location in the soil log. The samples for the direct shear test were extracted from a depth of 0.3 m to 0.5 m by a Shelby tube as shown in Figure 3.2.

The soil stratigraphy consisted of approximately 0.2-0.3 m of black organic topsoil underlain by plastic clay. The topsoil was moist and sandy with some soft grey clay intermixed. The remaining soil was primarily brown clay with fine sand, silt lenses and silt nodules. The high plastic clay ranged from soft near the surface to firm at depths of 3.0 m. Most of the site had water on the surface indicating high water table and poor drainage. Deciduous trees lined the first 200 m of the site while the remaining 100 m was lined with coniferous trees. The soil borehole log is shown in Appendix 1.

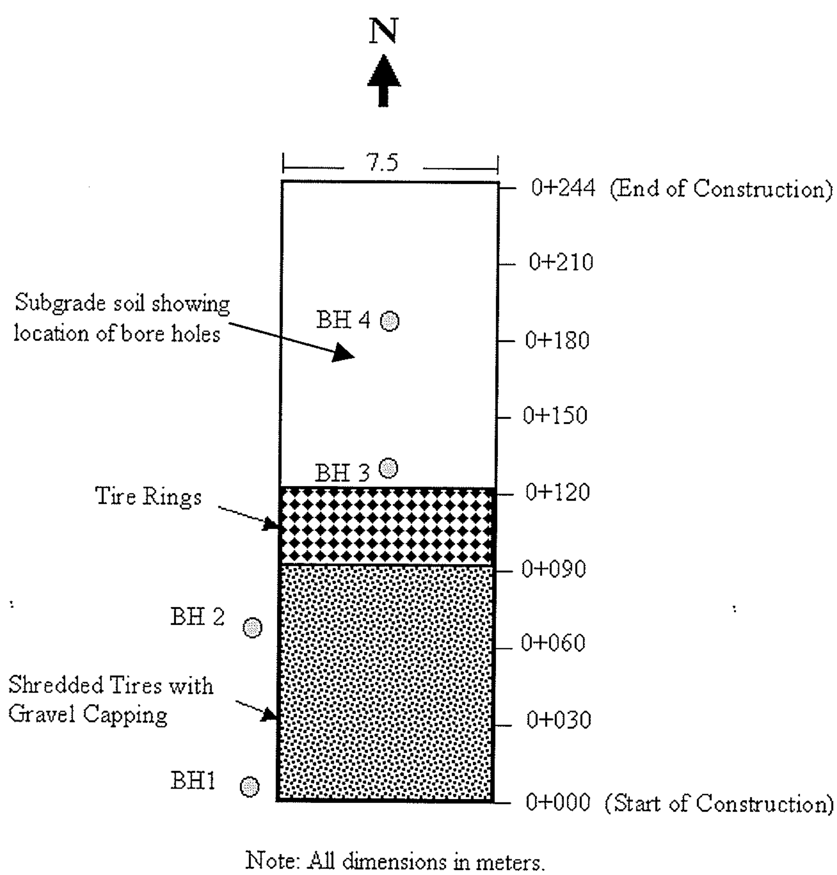


Figure 3.1 Plan view of construction site showing location of boreholes

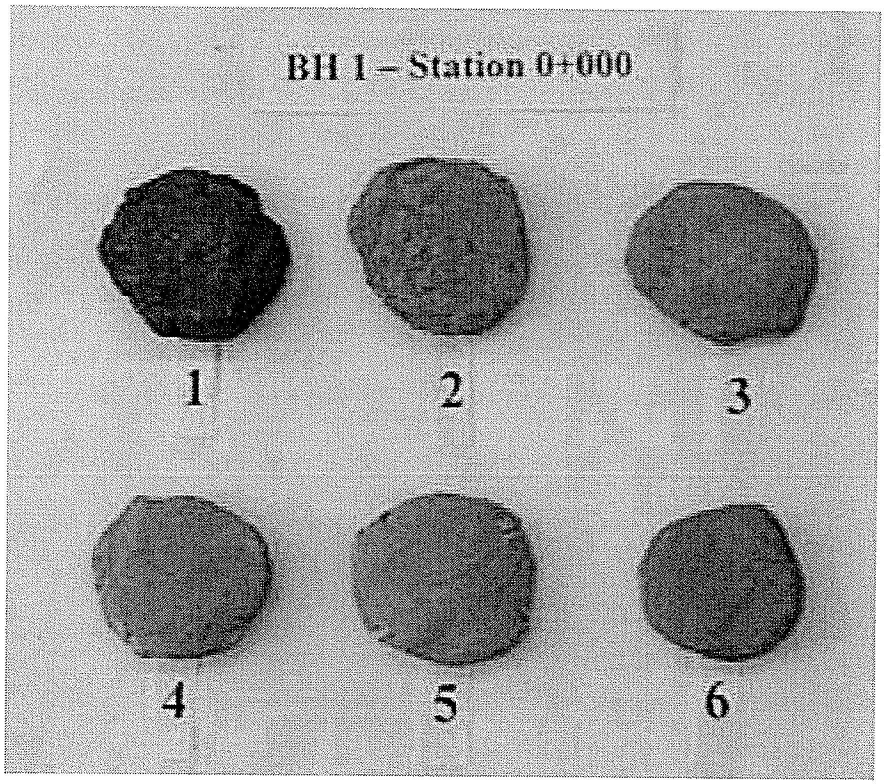


Figure 3.2 Typical soil samples obtained from site for soil testing

3.2.1 Engineering Properties of Subgrade Soil

3.2.1.1 Moisture Content

The moisture content indicates the amount of water present in a sample of soil and is calculated by dividing the mass of water by the mass of solids in a soil sample. A small portion of each sample from the site was oven dried and the water content was determined. The results are outlined in Table 1, Appendix 2.

3.2.1.2 Grain Size

The frequency of different sized particles in a given soil sample is called its grain-size distribution. The hydrometer grain size analysis is a common method of estimating the distribution of soil particle sizes from 0.075 mm to the 0.001 mm. The hydrometer analysis also has value in identifying particle sizes less than 0.020 mm in frost susceptible pavement subgrade. For example, gravels with 5 percent passing the 0.020 mm sieve are susceptible to frost action (Hoel and Garber, 1996). The hydrometer grain size analysis was performed on all three-soil mixtures in accordance with ASTM D 422. The specific gravity was estimated at $G_s = 2.65$. The clay fraction of the soil is defined as the percentage of particles finer than 0.002 mm. Summaries of the soil fraction in each of the mixtures are given in Table 2, Appendix 2.

3.2.1.3 Atterberg Limits

Fine-grained soils with low moisture contents behave as a solid. As the moisture content increases the material becomes more plastic giving the soil the ability to undergo unrecoverable deformation at a constant volume without cracking or crumbling. At very high moisture contents, the soil begins to flow as a viscous liquid. The water contents at which the soil changes from one state to another are defined as Atterberg limits. Two of these limits are the liquid limit (w_L) and the plastic limit (w_P). The liquid limit is the moisture content at which soil placed in a brass cup will close a 12.7 mm groove when dropped 25 times from a height of 10 mm at a constant rate of 120 drops/minute. The plastic limit is the moisture content at which the soil will crumble when rolled to a diameter of 3 mm with the tips of the fingers. Plasticity index, the difference between the liquid limit and plastic limit, is the moisture content range over which the soil behaves in its plastic state (Bowles, 1992). Table 3 Appendix 2 summarizes the results from the laboratory testing of the liquid and plastic limits. These limits are not only important for the classification of soils, but also for checking the consistency or variability between soils.

3.2.1.4 Soil Description and Classification

A soil description details the type and characteristics of the material that makes up the soil whereas a soil classification allocates the soil into a group based on the material characteristics only. The material characteristics include the liquid and plastic limits and the particle size distribution. The soil was visually classified in the field and in the laboratory. The soil samples were classified using both the AASHTO and Unified Soil Classification systems.

AASHTO System

The AASHTO soil classification system uses group classifications A-1 to A-3 for granular materials (35 % or less passing the No. 200 sieve), A-4 to A-7 for silt-clay materials (more than 35% passing the No. 200 sieve) and A-8 for peat (Bowles, 1992). Each of these groups is divided into subgroups to further classify the soil. When there is more than one type of soil in a subgroup, the material is further classified by calculating the group index (GI). The GI depends on the percent passing the No. 200 sieve, the liquid limit (w_L) and the plasticity index (I_P). Soils with a high GI will be of poorer quality than those with a lower GI. Materials classified, as A-2-6, A-2-7, A-4, A-5, A-6, A-7-5, and A-7-6 are not suitable subgrade materials and would require a layer of a subbase material for strength (Hoel and Garber, 1996). The soil mixtures obtained from the test site were classified as shown in Table 4 Appendix 2. The group A-7 indicates clayey soils while subgroups 5 and 6 are based on the plasticity of the material. From the AASHTO classification system all three-soil mixtures were unsuitable as a subgrade material in its natural state.

Unified Soil Classification System (USCS)

The USCS uses group symbols to classify soil material into six categories: gravel (G); sand (S); silt (M); clay (C); organic soils (O) and peat (Pt). For coarse-grained soils these categories are further broken down into gradation subgroups: well graded (W) and poorly graded (P). Fine-grained soils, on the other hand, are subdivided into two plasticity categories: high plastic (H) and low plastic (L). Most fine-grained soils such as silt, low-plastic clay, and organics are unsuitable subgrade materials due to their liquid limit, plasticity index and frost susceptibility (Bowles, 1992). On the whole soil was high plasticity clay.

3.2.1.5 Shear Strength

The shear strength of soils is important for road design as soil masses usually fail in shear under highway traffic loads (Hoel and Garber, 1996). The shear strength depends on the cohesion and internal angle of friction of the soil mass. The shear strength of a soil is defined as:

$$\tau = c + \sigma \tan\phi \qquad (2.1)$$

where

τ=shear stress

c= cohesion

σ=normal stress

ϕ= internal angle of friction

The cohesion and the internal angle of friction vary with material type. Cohesion is an important factor in the shear strength of fine-grained materials such as clay and silt as it provides much of the shear strength. Coarse-grained materials, such as sand and gravel, have no cohesion, but a high angle of internal friction that resists sliding of particles over each other.

The direct shear test was used to determine the shear strength parameters of the soil at the site. A sample of undisturbed soil was collected in a thin walled Shelby tube and trimmed to fit a circular metal shear box that splits horizontally at mid-height. Porous plates were placed at the top and bottom of the specimen to allow free drainage of excess pore water. This type of direct shear test is categorized as a consolidated-drained test. In this test, a normal (vertical) force is applied to the top of the specimen and no shear force is applied until settlement has stopped. A shear force is then applied very slowly so small pore water pressures can be ignored. Two soil samples were tested to determine the cohesion and internal angle of friction. Soil mixture type A best represented these samples. The first sample was normally loaded at 25, 50 and 75 kPa and the second sample was loaded in the reverse order. The samples were allowed to consolidate at each new load. A motor was used to activate the horizontal shearing load and displacement. The results obtained from these tests are shown in Figure 3.3. The results showed cohesion of 2.9 kPa and angle of internal friction of 26° (Klymchuk et al, 1999).

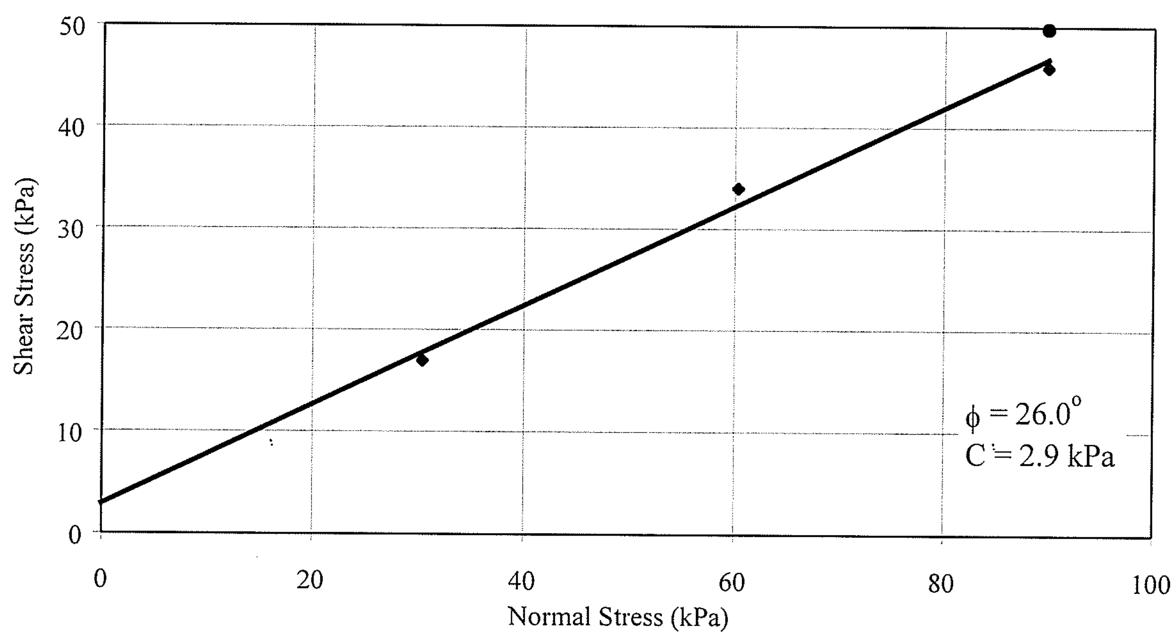


Figure 3.3 Shear strength of subgrade soil mixture

3.2.2. Summary of Soil Investigation

From the geotechnical investigation, it is evident that this soil was not a suitable subgrade for conventional construction. The California Bearing Ratio (CBR) for this soil was expected not to exceed 2%. A thick layer of subbase material was required to adequately reduce the stresses and settlements of the subgrade under traffic conditions. However, the loading from a thick subbase layer would itself produce significant and probably irregular settlements in the subgrade soil. There were three possible alternatives to improve the subgrade soil prior to construction of a road embankment. These included: (1) replacing the existing subgrade with a compacted borrow that is better suited for use as a subgrade; (2) stabilizing the soft subgrade; and (3) constructing a lightweight road embankment. Each of the three alternatives would limit the progressive settlement of the soft subgrade and provide the strength required to adequately distribute the load.

3.3 Road Embankment Construction

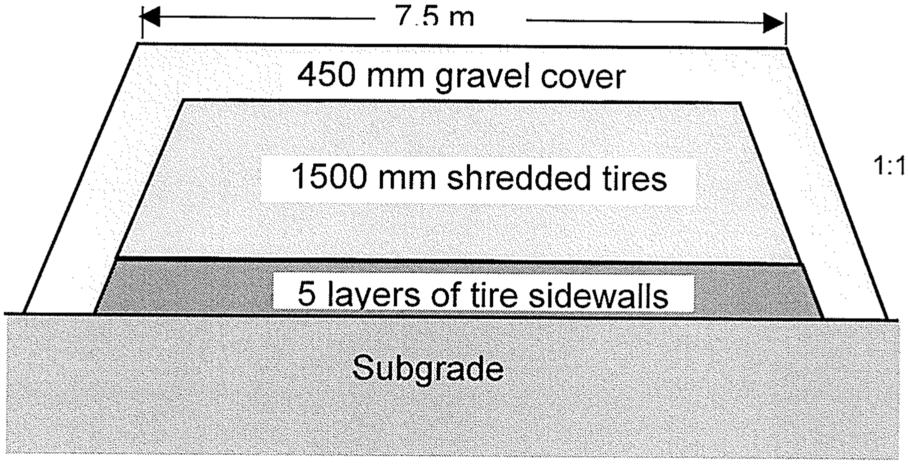
The following factors were considered in the construction of the 2.15 m high gravel surfaced tire shred embankment.

- Subgrade soil conditions
- Available sizes of the tire shreds
- Placement method of the tire shreds

The 300-m long road embankment was constructed in July 1999. Initially five layers of the whole tire sidewalls were manually placed on the subgrade in overlapping pattern to provide a clear working surface and to elevate tire shreds above the ground water table, Figure 3.4. Then 300-mm tire shreds were hauled to the site unloaded directly over the sidewalls and were spread to the desired thickness of 1500 mm with a backhoe, Figure 3.5. The tire shreds were compacted with five passes of a small bulldozer, with passes perpendicular and parallel to the centre line of the road, and were finally covered with 450 mm thick gravel fill (25 mm nominal maximum size) as shown in Fig 3.6. Slope stability of the embankment was not deemed to be a concern because of the high friction angle of tire shreds (Bosscher and Edil, 1994).

Figure 3.4 Placement of whole tire sidewalls directly over subgrade

Figure 3.5 Delivery of tire shred to construction site.



Typical cross section of tire shred embankment

Figure 3.6 Tire shred embankment during construction

CHAPTER 4

AUTOMATED TEMPERATURE MEASUREMENT AND GROUND WATER QUALITY TESTING

4.1 Automated Temperature Measurement

Soil thermal properties are of great importance in many engineering projects where heat transfer takes place in soils. Heat transfer in tire shreds plays an important role in road construction over frost susceptible soils. An understanding of the thermal behaviour of tire shreds is necessary. Thermal behaviour of tire shreds is important in determining its function as a foundation material for roads in cold regions. Development of thermal behaviour of tire shreds allow engineers and practitioners to determine the thickness of tire shred embankments and calculate depth of frost penetration which give guideline for reducing the thickness of base course in roads in frost-affected areas. In frost-affected areas the depth of frost penetration not the load controls road structure (Eaton et al, 1994).

For this purpose field-monitoring program was carried out to monitor ground thermal regime and develop the thermal behaviour of tire shreds.

4.2 Embankment Instrumentation

Thermocouples are the most widely used sensors for temperature measurement. A thermocouple consists of two dissimilar metals joined together at one end that produces small thermoelectric voltage when the end is heated. The change in thermoelectric voltage by a thermocouple is interpreted as a change in temperature. Thermocouples are available in different combinations of metals or calibrations. Each calibration has a different temperature range and environment although the maximum temperature varies with the diameter of the wire used.

Thirty-two copper constantan thermocouples in four 50-mm PVC pipe casing were used in the temperature-monitoring program. Strings of thermocouples were attached to pipe casings for the evaluation of the thermal behaviour of tire shreds. The thermocouple strings were 3 m long. The gaps between the thermocouples and top and bottom of the strings were sealed. Due to the topography of the site and economic constraints, no control section of road, made of conventional gravel materials, was used in this study. Thermal response of the tire shreds was compared with natural ground (clay). Nine thermocouples in the tire shred embankment and seven thermocouples in the adjacent roadside were placed with a uniform spacing of 343 and 457 mm respectively, Figure 4.1. The spacing of thermocouples was selected based on the capacity of the data acquisition (DAQ) system. The DAQ system had 16 bit analog inputs, signal amplification and cold junction compensation to provide an accurate temperature measurement within 0.1°C.

Thermocouples were connected to the data acquisition system, placed in a heated and insulated data collection box. Due to the severe climatic conditions on site, the computer and DAQ system were placed in an insulated data collection box. Two openings were made on each side of the data collection box for connection of thermocouple into DAQ system. In order to eliminate the entry of air and moisture into the box, steel elbow pipes were inserted into the opening after connecting the thermocouples to the DAQ system. The gaps between the thermocouple and elbow pipes were sealed. In order to maintain an acceptable operating temperate environment for the computer and DAQ system, the data collection box was completely insulated using Styrofoam insulating sheets. An electric heater was placed to maintain a temperature in the range of 10 to 25°C inside the box as shown in Fig 4.2.

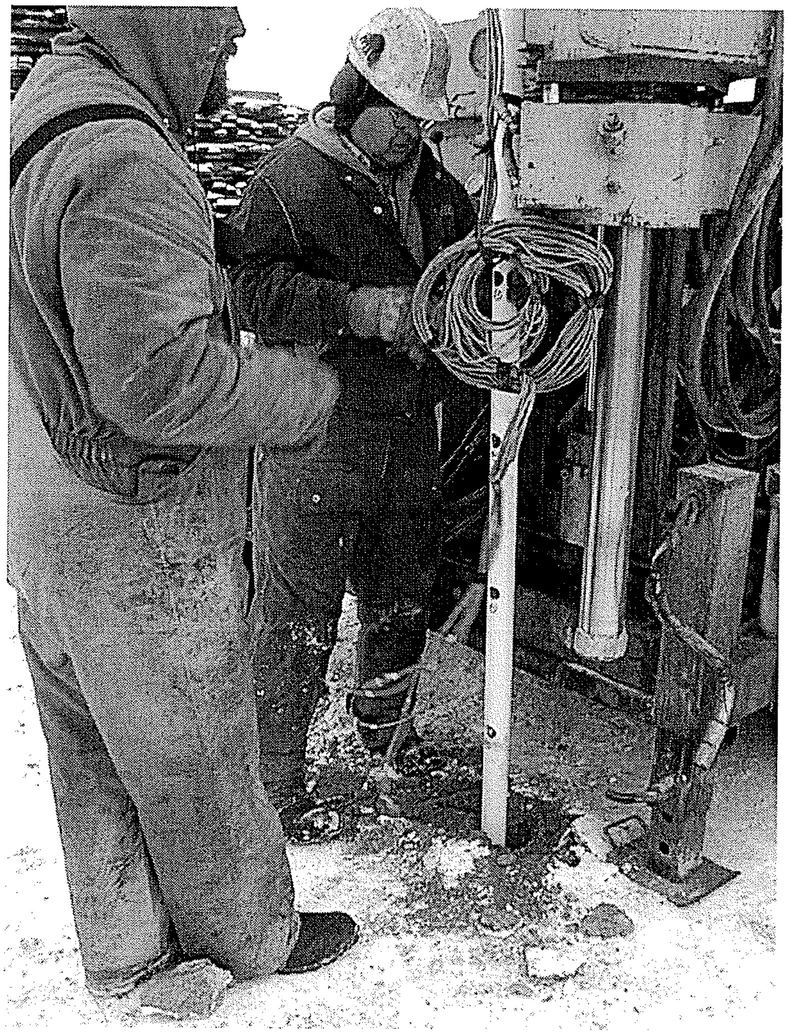


Figure 4.1 Placement of thermocouple strings in tire shred embankment

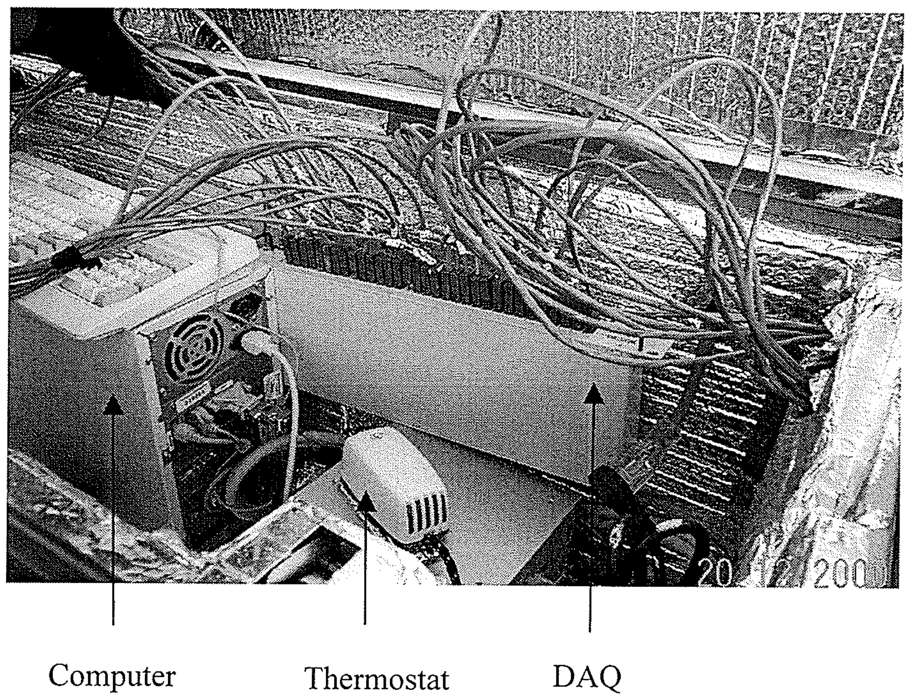


Figure 4.2 Data collection box with computer and heater

A plan and cross-sectional view of tire shred embankment site showing an approximate location of thermocouples in ground and in tire shred embankment with DAQ and computer is shown in Figure 4.3.

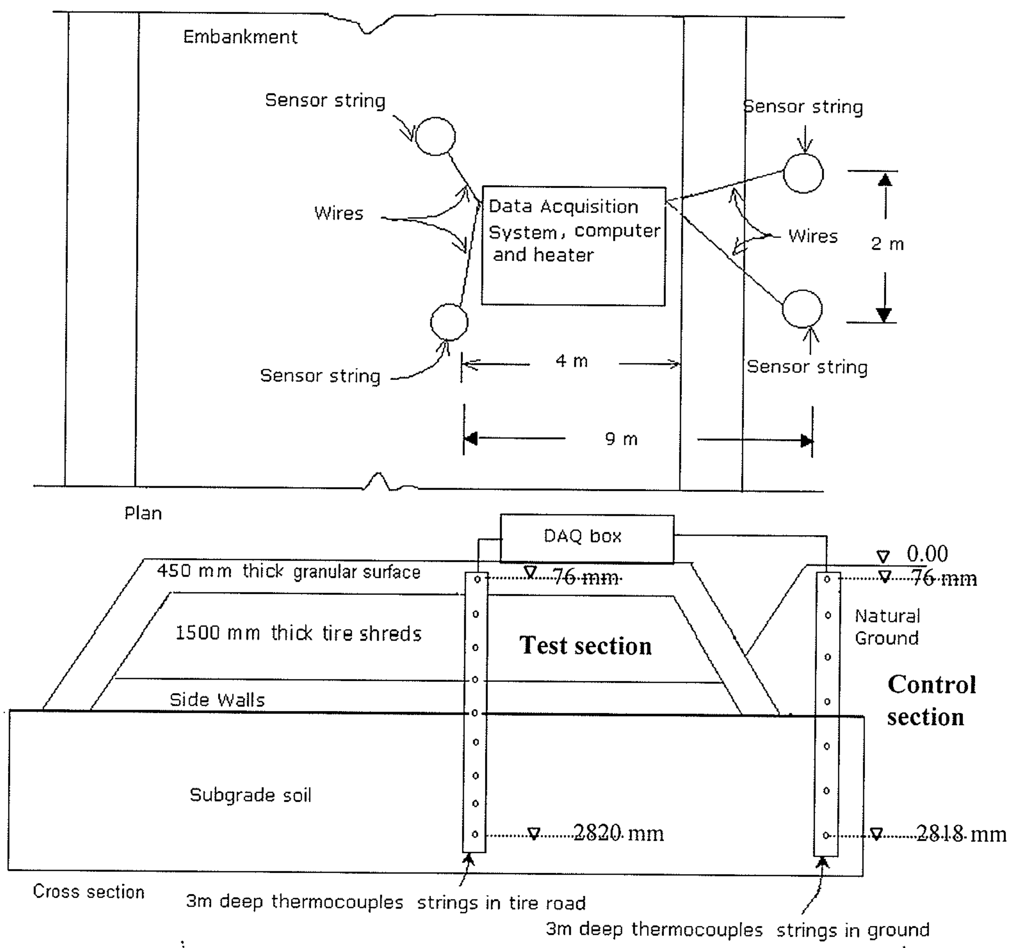


Figure 4.3 Instrumentation plan and cross section of project site

4.3 Data Collection

The temperature-monitoring program was started in November 2000. The DAQ system recorded a temperature reading for each sensor every hour. Temperature measurement was performed for the winter and spring seasons, Dec 2000-May 2001. Periodically, a computer monitor was connected to the computer in the data collection box on site, and the stored data was transferred to disks for subsequent analysis.

4.4 Data Analysis

4.4.1 Depth of Frost Penetration

The climate has an important influence on the behaviour and performance of the various materials in the road structure. The two climatic factors of major significance are temperature and moisture (Wright and Paquette, 1987). One of the climate related problems of interest in many regions of the world is that of damage caused to pavement structure by the freezing and thawing of subgrade and bases during winter and spring seasons. This phenomenon is called frost action which is the distortion or expansion of the subgrade soil or base material during the period when freezing temperatures prevail and when the ground is frozen to a considerable depth (Wright and Paquette, 1987). From this data, the average depth of frost penetration is summarized in Fig 4.4. It is seen that the depth of frost penetration beneath the tire shred embankment ranged from 560 mm to 1250 mm. In contrast, in natural ground, the depth of frost penetration ranged from 340 mm to 780 mm (Khan and Shalaby, 2002). The value of average freezing index in Winnipeg region is 1900°C days. Several possible reasons for greater depth of frost penetration in the tire shred embankment compared to the natural ground are

1. Low water content of the tire shreds as compared to high water content of the natural ground.
2. High void ratio of the tire shred embankment.
3. The presence of a thicker blanket of snow on top of the natural ground compared to the tire shred embankment.

Previous research has shown that depth of frost penetration in gravel is larger than the tire shreds (Eaton et al, 1994).

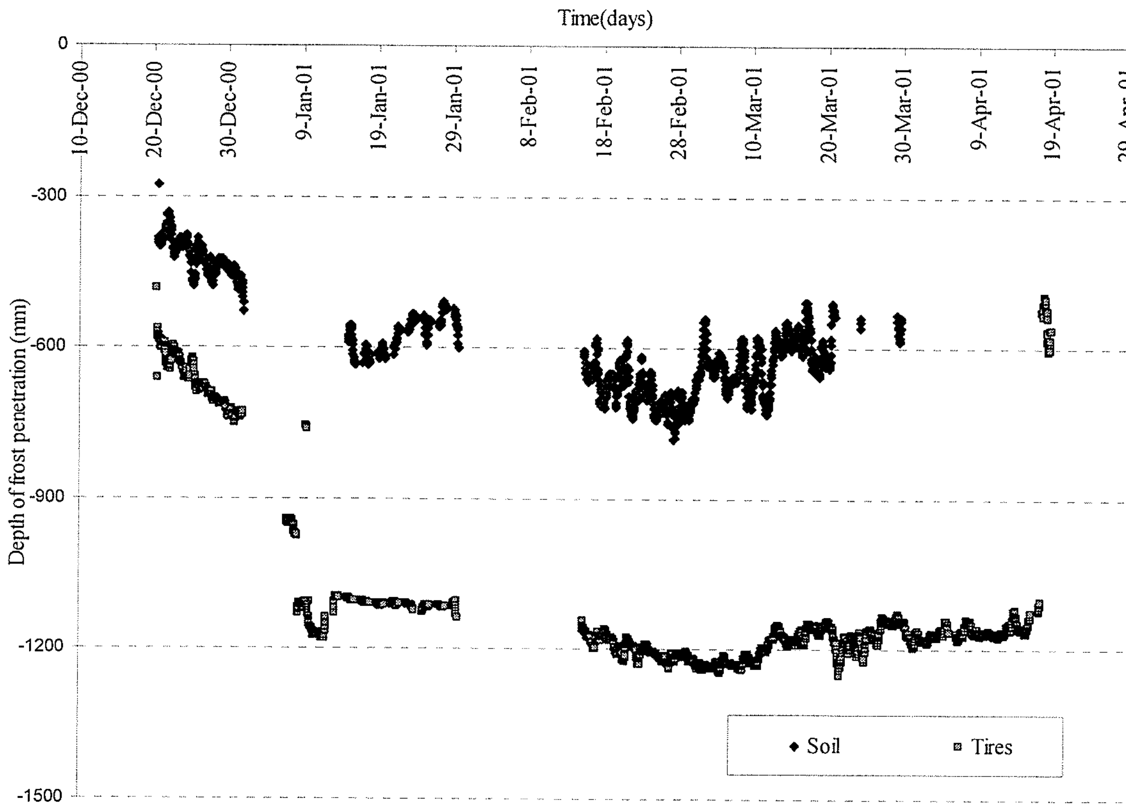


Figure 4.4 Depth of frost penetration in natural ground and tire shred embankment, Dec 2000-May 2001

4.4.2 Temperature Gradient

Considering a prismatic element of soil having a length "L" as shown in Fig 4.5, the temperature gradient is defined as

$$\theta = \frac{(T2 - T1)}{L} \tag{4.1}$$

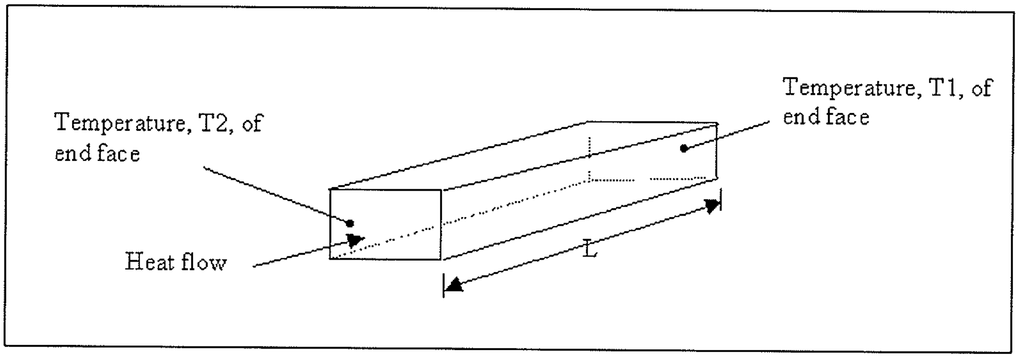


Figure 4.5 Illustration of temperature gradient through a prismatic element

Typical thermal gradients of the natural ground and the tire shred embankment, obtained from data as measured from December 2000 to May 2001, Fig 4.6, shows that the surface temperature in the tire shred embankment is lower than the natural ground while the base temperature is essentially the same at both sections indicating a rapid resistance to the frost within the tire shreds fill. Therefore the thermal gradient in tire shreds is higher compared to the gradient in the natural ground.

4.4.3 Thermal Conductivity

The thermal conductivity is defined as the amount of heat passing in unit time through a unit cross sectional area under a unit temperature gradient applied in the direction of the heat flow (Farouki, 1986) and is normally expressed as W/m·°C. In the range of water content (5 to 10 percent) and dry densities (2000-2200 kg/m^3) commonly encountered in embankments and road base courses, thermal conductivity is very sensitive to moisture content and soil type (WSDOT, 1995). Thermal conductivity governs steady state conditions and can be estimated by the following linear steady state equation (Farouki, 1986).

$$Q = K\left(\frac{\partial T}{\partial Z}\right) \tag{4.2}$$

Where

Q=heat flow through soil

K=thermal conductivity of soil

$\frac{\partial T}{\partial Z}$ =temperature gradient in vertical direction

For steady state conditions, a constant thermal gradient exists through each layer of uniform material and the heat flow through each layer of soil is assumed to be equal. Therefore the thermal conductivity of tire chips can be estimated from the thermal conductivity of underlying soil (Humphrey, 1997). Steady state method was used to determine the thermal conductivity from the subsurface temperature measurements. For this analysis, it was assumed that the heat flow had reached steady state conditions by mid-February 2001, which can be justified by the examination of the subsurface temperature data. Figure 4.7 shows a schematic of the tire shreds embankment where a linear temperature gradient exists through tires and underlying soil. The latent heat of subgrade soil, $Q_{s,}$ is the heat of soil moisture, which is released causing the freezing of soil. While Q_t is the heat conducted through the tire shreds layer. Thus

$$Q_s=Q_t \tag{4.3}$$

$$K_s.\ \theta_s = K_t.\ \theta_t \tag{4.4}$$

Where

Q_t, Q_s = heat flow through tire shreds and underlying soil

K_t, K_s = thermal conductivity of tire shreds and underlying soil

θ_t, θ_s = thermal gradient of tire shreds and underlying soil

The thermal conductivity of underlying clay soil was selected from design charts for moisture content and dry density of 25 percent and 1500 kg/m^3 respectively for unfrozen conditions (Department of Defence, 1966, Kersten, 1949) and was found to be 1.416 W/m·°C. The thermal gradient for tires and underlying soil was obtained as 10°C /m and 2°C/m respectively from subsurface temperature data as summarized in Fig 4.6. The thermal conductivity of tire shreds, K_t , is found to be 0.2832 W/m·°C which is five times lower than thermal conductivity of clay for dry density of 1500 kg/m^3 and moisture content of 25 percent (Shalaby and Khan, 2002a). Thermal conductivity of tire chips is eight times lower than thermal conductivity of gravel (Humphrey, 1996).

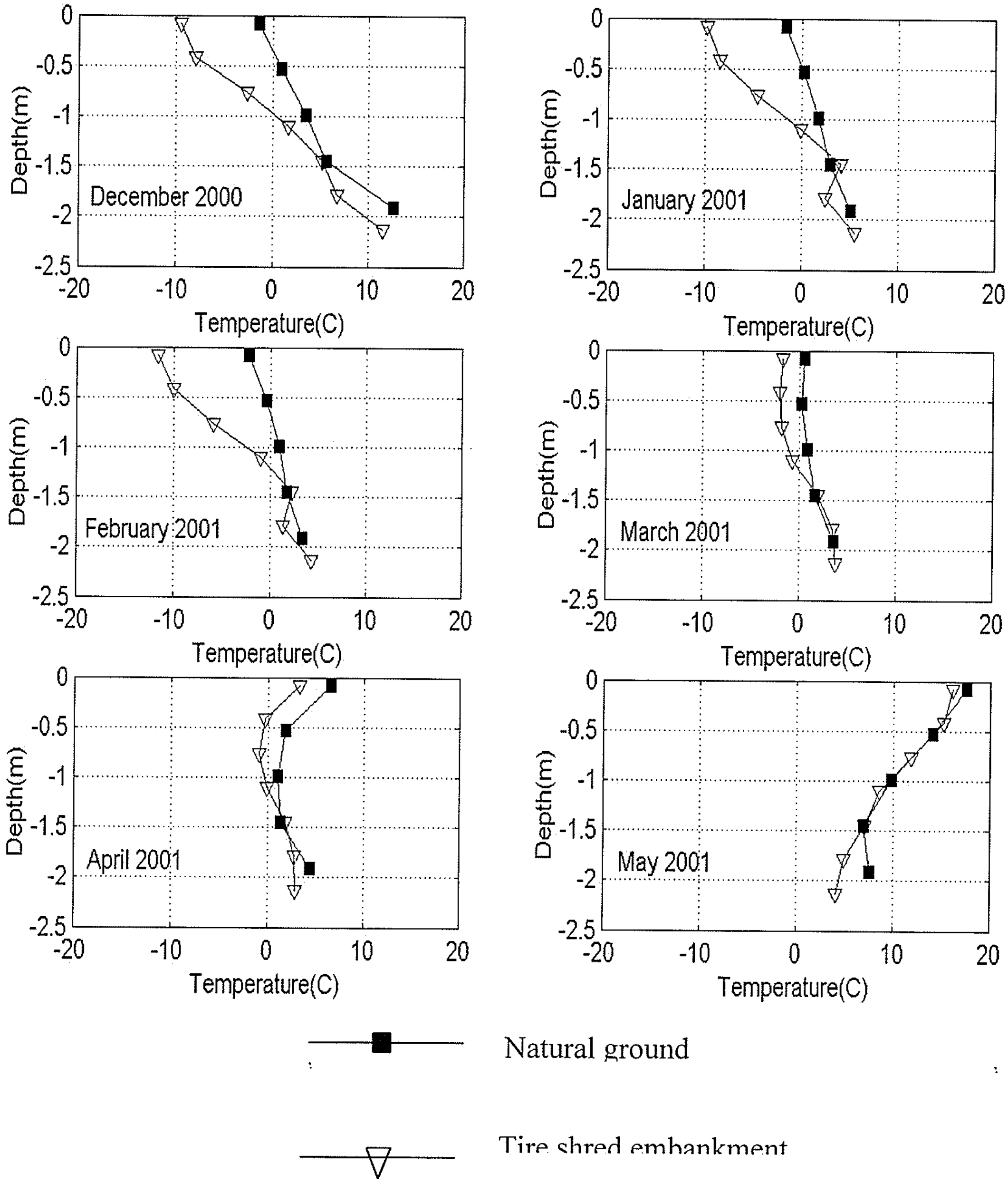


Figure 4.6 Thermal gradients of the natural ground and the tire shred embankment

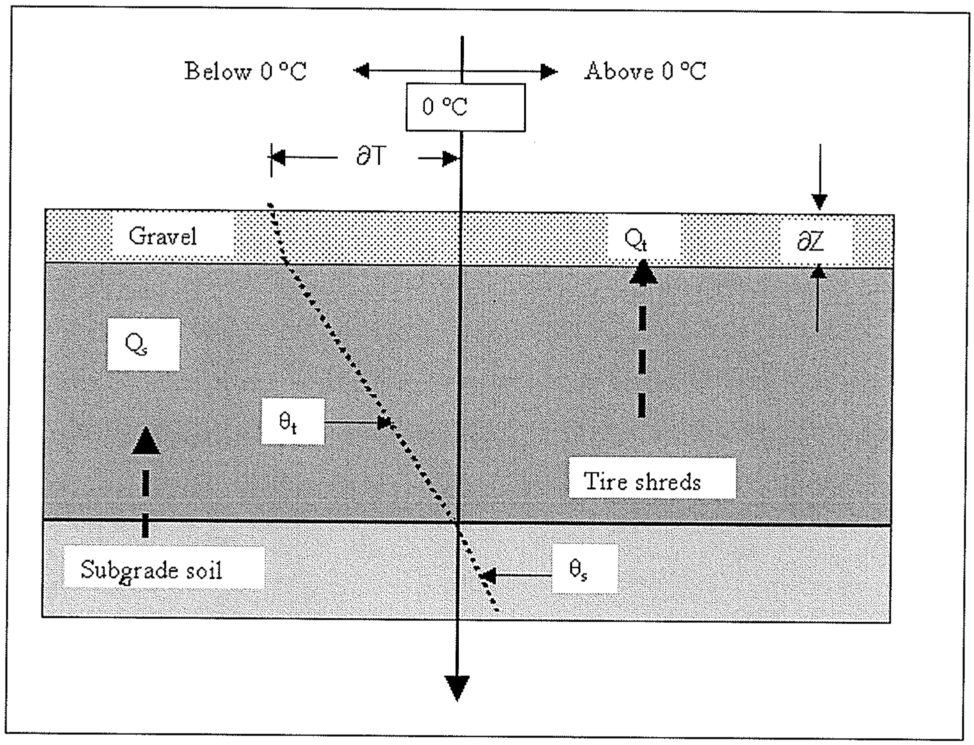


Figure 4.7 Schematic of heat flow and thermal gradient in tire shred embankment

4.4.4 Temperature with Time at Various Depths

Economic road design is mainly dependent on the thermal properties of construction materials. Thermal behaviour of tire shreds must be closely linked with a discussion on the variation of temperature in tires and in soil at increasing depth below the surface and throughout the winter/spring cycle of the year (Dec 2000-May 2001). This basic characteristic of tire shreds might appear at first sight to be a simple matter however due to many variable factors involved; the problem is actually more complex. The use of modern measuring instruments in the field-monitoring program of this study greatly simplified this complex behaviour of tire shreds.

Various factors, which may affect the soil temperature, can be divided into internal and external factors (HRB, 1952). Specific gravity, thermal conductivity, moisture content and surface cover are some of the internal factors. Air temperature, sunshine, wind and precipitation and snow cover are some of the external factors. The temperature profiles in natural ground and tire shred embankment at various depths are shown in Fig 4.8 and 4.9 respectively. In winter, it is seen that there is little variation in temperature in natural ground with increasing depth. However in tire shred embankment, the variation is more prominent upto a depth of 762 mm and less prominent with increasing depth and the temperature is lower than natural ground.

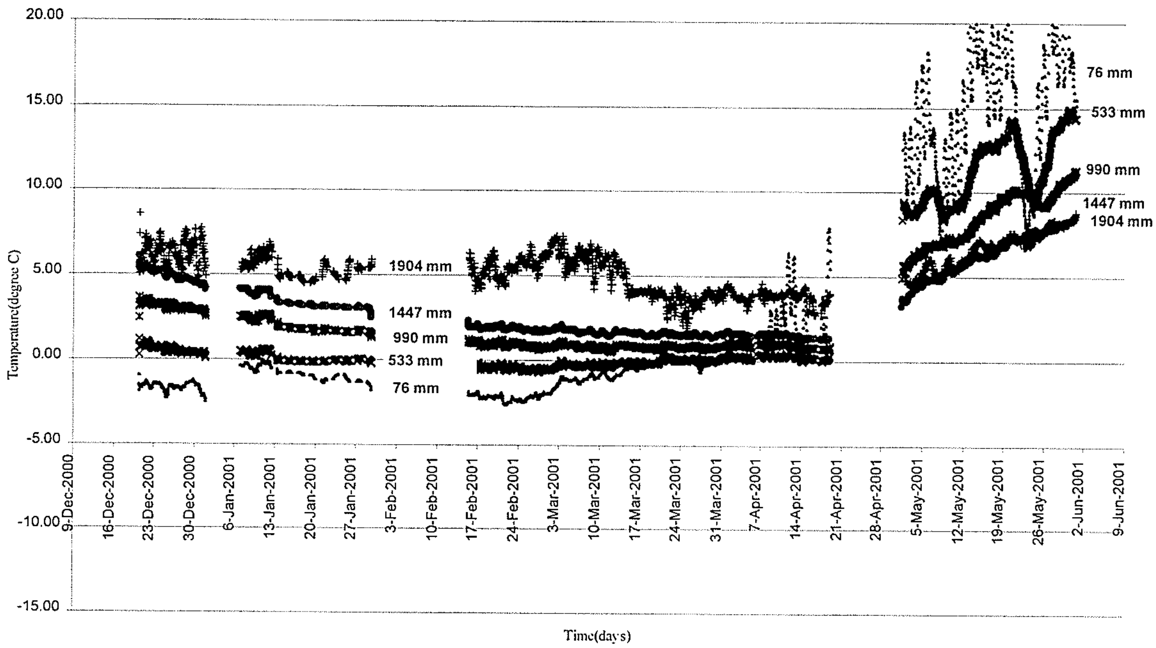


Figure 4.8 Temperature profiles from the thermocouples strings in the roadside (clay soil)

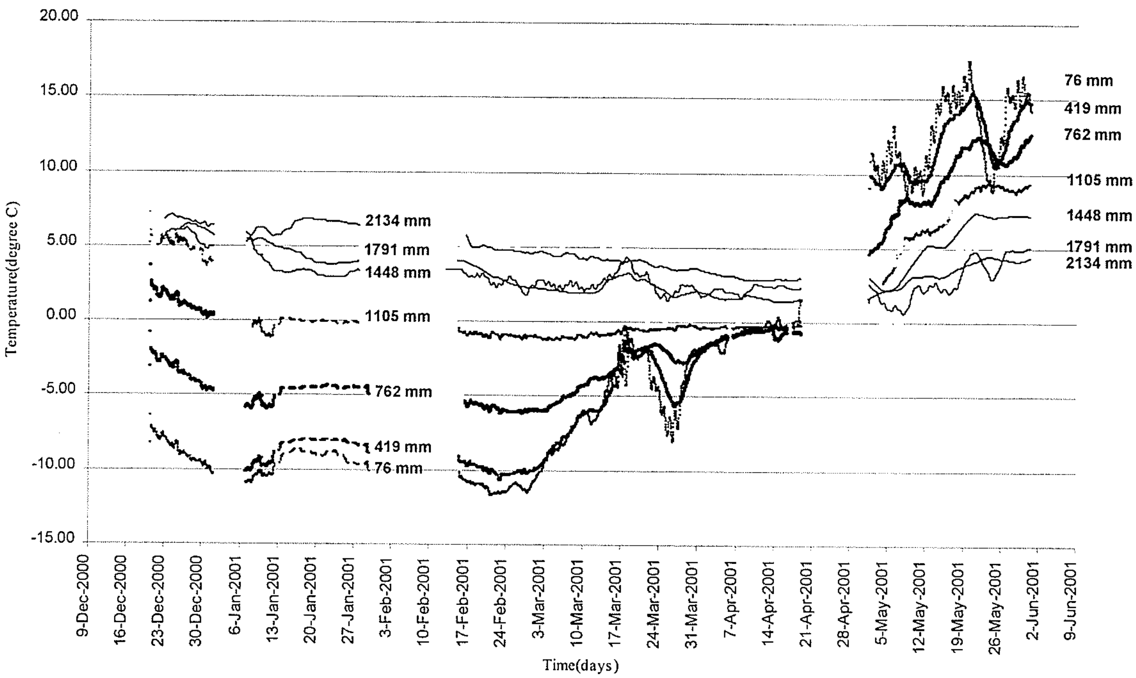


Figure 4.9 Temperature profiles of tire shred embankment

4.5 Ground Water Quality

4.5.1 General

Water in nature is rarely pure and contains some impurities. Water has four measurable properties that are commonly used to characterize its chemistry. These are pH, buffering capacity, general hardness and salinity.

Agencies throughout the world including United States Environmental Protection Agency (EPA) and Canadian Council of Ministers of the Environment (CCME) have set standards for water quality. EPA has standards for contaminants that may occur in drinking water and cause a risk to human health. These contaminants fall into two categories according to the health effects that they cause. Severe effects occur within hours or days of the time that a person consumes a contaminant. A person can suffer acute health effects from almost any contaminant if they are exposed to extraordinarily high levels. In drinking water, microbes, such as bacteria and viruses, are the contaminants with the greatest chance of reaching levels high enough to cause acute health effects. Persistent effects occur after a person consumes a contaminant at levels over safety standards for many years. The drinking water contaminants that can have chronic effects are chemicals (such as disinfection by-products, solvents, and pesticides), radionuclides (such as radium), and minerals (such as arsenic). Examples of the chronic effects of drinking water contaminants are cancer, liver or kidney disease (EPA, 1996).

The EPA has established national primary drinking water regulations in the United States that set mandatory water quality standards for drinking water contaminants. These are enforceable standards called maximum contaminant levels, which are established to protect the public against consumption of drinking water contaminants that present a risk to human health. In addition, EPA has established national secondary drinking water regulations that set non-mandatory water quality standards for contaminants. EPA does not enforce these secondary maximum contaminant levels. They are established only as guidelines to assist public water systems in managing their drinking water for aesthetic considerations, such as taste, colour and odour. These contaminants are not considered to present a risk to human health at the secondary level. There are a wide variety of problems related to secondary contaminants. These problems can be grouped into three categories: Aesthetic effects such as undesirable tastes or odours; cosmetic effects which do not damage the body but are still undesirable; and technical effects which damage the water equipment or reduced effectiveness of treatment for other contaminants (EPA, 1996).

In 1987, the Canadian Council of Resource and Environment Ministers (CCREM), the forerunner of the Canadian Council of Ministers of the Environment (CCME), published Canadian water quality guidelines, which provided national guidelines for major water uses in Canada. In addition to being highly successful in Canada, these guidelines have received international recognition by the United Nations and the World Health Organization as models for environmental quality standards. These are currently being used in around 45 countries around the world. Canadian Environmental Quality Guidelines (EQGs) represents the result of about a decade of national science-based guideline development work in Canada (CCME, 1999). These guidelines also characterize the water quality standards in terms of primary and secondary standards as described before.

4.5.2 Effects of Tire Shreds on Ground Water Quality

Tire shreds placed above the water table have a negligible impact on water quality. This conclusion was drawn from a five-year field study conducted in North Yarmouth, Maine (Humphrey and Katz, 2000). Summary and evaluation of existing literature on the effect of tire shreds on ground water quality also concluded that recycled rubber derived from scrap tires is a safe recycled material (Liu et al, 1998).

In order to investigate the effect of tire shreds on water quality, inorganic and organic water quality testing were performed for the tire-shred embankment on 15/03/2001 and 20/04/2001 (Khan and Shalaby, 2001).

4.5.2.1 Inorganic Water Quality

The inorganic water quality tests were performed for unfiltered samples for metals, as shown in Table 4.1, and a standard water quality analysis was performed involving measurement of pH, Calcium, Magnesium, Sodium, Potassium, Iron, Manganese, Chloride, Nitrate and Nitrite, Sulphate and hardness of water.

Of the inorganic containments in ground water, those of greatest concern are Nitrates, Ammonia and trace metals. Arsenic, Cadmium, Chromium, Lead, Zinc and Mercury are metal pollutants of major concerns in ground water. Many of these metals arise from industrial practices and are toxic to humans, especially Cadmium, Lead and Mercury (EPA, 1996). The inorganic water quality results are shown in Table 4.1 and are compared with the maximum values obtained during spring of 5 years field study conducted in Maine, USA (Humphrey and Katz, 2000) and Canadian Council of Ministers of the Environment (CCME), Environmental Quality Guidelines (EQGs), (CCME, 1999). These results show that concentrations of Aluminium, Iron and Manganese are higher than the recommended values with a pH and hardness of 7.65 and 498 mg $CaCO_3$/L respectively but are of less concern, as these are secondary parameters in the EQGs.

Design guidelines have been established to minimize the exposed steel content in tire shreds to decrease the concentration of iron in water. Federal HighWay Administration (FHWA) in the Unites States has given guidelines which states that tire shreds shall have less than 1% by weight of metal fragments that are not at least partially encased in rubber and metal fragments that are partially encased in rubber shall protrude no more than 25 mm from the cut edge of the tire shred on 75% of the pieces and no more than 50 mm on 100% of the pieces (Dickson et al, 2001).

Table 4.1 Inorganic water quality analysis

Analyte	Humphrey [1] (mg/L)	Canadian Limit [2] (mg/L)	As tested on 15/03/01* (mg/L)	As tested on 20/04/01 (mg/L)
Aluminium	0.50	0.2	1.53**	0.055
Barium	0.23	1	0.0780	0.0454
Calcium	500	1000	120	83.2
Chromium	0.75	0.05	0.0024	< .0009
Iron	28	0.3	5.75**	0.159
Magnesium	160	No Limit	54.7	31.3
Manganese	19	0.05	0.714**	0.033
Sodium	800	200	11.5	5.5
Zinc	1.25	5	0.0868	0.0098

1. Results from a five year study (Humphrey and Katz, 2000).

2. CCME, 1999.

* With a pH and hardness of 7.65 and 498 mg $CaCO_3$/L respectively
** Canadian limit exceeded

4.5.2.2 Organic Water Quality

In organic testing the compounds being monitored are toxic to biotic systems or may, in sufficient amounts, degrade the quality of soil, water and air. These compounds were total extractable and purgeable hydrocarbons including Benzene, Toluene, Ethyl benzene and Xylenes (BTEX). These results showed that the level of organics is below the test method detection limits as shown in Table 4.2.

Table 4.2 Organic water quality analysis

Analyte	Canadian Limit * (mg/L)	As tested on 20/04/2001 (mg/L)
Benzene	0.005	< 0.001
Toluene	0.024	< 0.001
Ethyl benzene	0.0024	< 0.001
Total Xylenes	0.3	< 0.001
Total purgeable	-	< 0.01
Total Extractable	-	< 0.1

* *CCME, 1999.*

In this water quality testing, a conservative analysis approach is used. Water samples were obtained from the surface water table, where chemical leachate was observed, and compared with the drinking water quality standards.

This field monitoring of the tire shred embankment constructed with tires above the water table indicates that insignificant adverse effects on ground water quality have occurred. The inorganic and organic water quality tests show that most of the determined parameters are within acceptable limits. The results are also consistent with the five year field study conducted in Maine, USA.

CHAPTER 5

DEFLECTION MEASUREMENT

5.1 Design of Road Embankments Using Tire Shreds in the Base Layer

The design of road embankment using tire shreds in the base layer depends on several factors, among which a proper characterization of load-deformation response of tire shreds is very important. Tire shreds are more flexible and compressible than granular materials and the relatively high deflection of the tire shreds is a concern in the construction of the road embankments. An important component of the design of tire shred embankments is the deflection of tire shreds.

Two fundamental properties are needed for the design of road structure, resilient modulus and Poisson's ratio. Base or subbase materials undergo deflections when subjected to repeated loads from moving vehicular traffic. Each time a load passes a road structure, the materials rebounds less than it had deflected under the load. After repeated loading and unloading sequences, each layer in a road structure accumulates only a very small amount of permanent deformations and most deformation is recoverable or resilient deformation (Tian et al, 1998). To explain this behaviour, researchers have used the concept of resilient modulus; M_R, which defines the recoverable deformation response of road materials under repetitive loading corresponding to given state of stress (Bosscher et al, 1994).

A satisfactory tire shred embankment design can be achieved by use of appropriate resilient moduli for tire shreds. The resilient modulus test cannot be run on pure tire shreds and the elastic modulus is estimated from the repetitive constrained modulus tests (Bosscher, 1994). Limited research work has been reported on the resilience response of tire shreds. To investigate the mechanical behaviour of three sizes of tire shreds and to develop design parameters for the design of tire shred embankments, field and laboratory deflection tests were performed to assess the resilience response of the tire shreds to various stress level and to measure the deflection of the tire shred embankment.

5.2 Field Deflection Measurement

5.2.1 Deflection Survey

Metal settlement plates (500 x 500 mm) were placed at several locations flush with the surface of the road to measure the compressibility of the tire shred embankment, Fig 5.1. A rod and level survey was performed to quantitatively evaluate the performance of the embankment under traffic loads. Initially, the as built elevations of the settlement plates SP1, SP2, SP3 and SP4, Fig 5.2, were recorded. Then the settlement plates were loaded by a stationary 21,000 kg dual-tandem axle load and the elevations were recorded. A final elevation was recorded after the removal of the load, Fig 5.3. The deflection of the road was obtained from the difference of initial elevation and the elevation under load. The rebound was measured from the difference of final and loaded elevations. Two loading and unloading passes were performed.

Figure 5.1 Section of tire shred embankment showing settlement plates

Figure 5.2 Field deflection survey

5.2.2 Results

Results of field deflection survey are shown in Fig 5.3 indicating an average of 15 mm and maximum of 25 mm deflection under the load, after one year of fill placement. These values are not of great concern for unsurfaced roads. An average instantaneous rebound of 11 mm and an average irrecoverable displacement of 7 mm were also recorded after two passes of the loaded truck (Shalaby and Khan, 2002b).

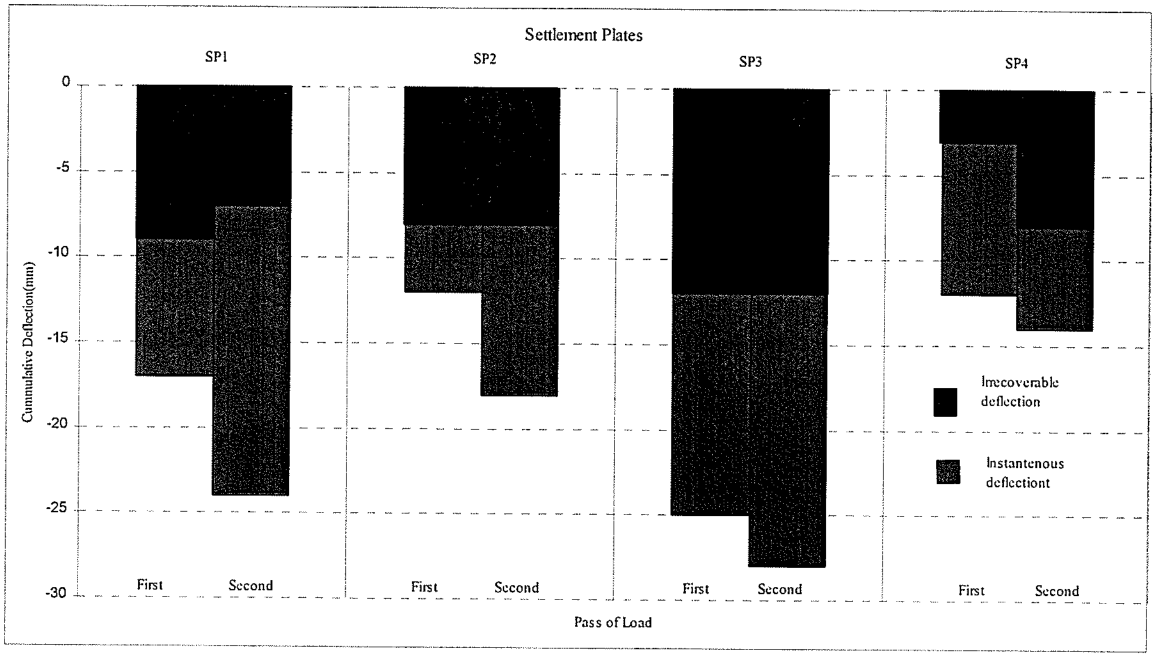


Figure 5.3 Field deflection of the tire shred embankment at four locations

5.3 Laboratory Deflection Measurement

5.3.1 Test Materials

Three sizes of the tire shreds, minus 300 mm, minus 150 mm and minus 50 mm, were examined for laboratory compressibility testing. These tire shreds were generally curved, irregular shaped and many had sharp, tangled and twisted steel reinforcing fibres protruding from their cut edges. The tire shreds were from a mixture of steel and glass-belted tires. The uncompacted density of the tire shreds was determined in the laboratory by first weighing an empty container and then weighing the container filled with tire shreds. The uncompacted density was obtained from the difference of final and initial readings and was found to be 343 kg/m^3, 355 kg/m^3 and 534 kg/m^3 for minus 300 mm, minus 150 mm and minus 50 mm tire shreds, respectively. The compacted density was also obtained by monitoring the compressibility of the shred sample during the application of the load.

5.3.2 Test Apparatus

Several laboratory tests have been performed to determine the response of the tire shreds to cyclic loading (Edil and Bosscher, 1992, Humphrey and Sandford, 1993, Hsieh and Wu, 2000). To investigate the behaviour of large size tire shreds and to address the resilience of the material for high stress level, cyclic loading/unloading constrained compression tests were performed using a servo hydraulic loading frame connected to a data acquisition system. The constrained tests were performed in a straight wall cylindrical steel container. The inside dimensions of the container were 900 mm in diameter and 1000 mm in height. A steel loading plate, 875 mm in diameter and 200 mm thick, was attached to the actuator. The plate was slightly smaller than the inside diameter of container to prevent jamming.

5.3.3 Testing Methodology

The tire shreds were placed in the rigid steel container. The inside of the container was lubricated, ASTM D 6270 (ASTM, 1998), to reduce the portion of the applied load that is transmitted by side friction from the tire shreds to the walls of the cylinder. However it should be stressed that in tests where a higher level of accuracy is required, both top and bottom stresses should be measured to compute the average vertical stress. The tire shreds were placed in a loose state in the cylinder up to a depth of 800 mm. The load was applied to the tire shreds at a constant rate of displacement of 10-mm/min. Repeated loading and unloading cycles were made. The tire shreds were unloaded at the same rate, Fig 5.4. The tire shreds were subjected up to 20 cycles of loading as shown in Figures 5.5, 5.6 and 5.7. In each test, computer directed the actuator to perform programmed test procedure and the values of load and vertical displacements were collected in a data file.

5.3.4 Experimental Results

Figure 5.8 shows the stress-strain response of the three sizes of the tire shreds after the deduction of the irrecoverable displacement caused by placing the shreds in a loose state in the cylinder. Irrespective of the shred size, initial compaction takes place in the first cycle of loading and stiffness of the tire shreds increases. A part of this deformation is irrecoverable and a significant rebound (resilience) occurs upon unloading. The subsequent loading-unloading cycles tend to have similar stress-strain response however with less resilience response than the first cycle.

5.3.5 Significance of Laboratory Deflection Measurement

The laboratory deflection test results were characterized in terms of the maximum strain obtained at 600 kPa stress level in the first cycle of loading. At this stress level, the strain was about 36.5, 38.5 and 41 percent for 50 mm, 150 mm and 300 mm tire shreds respectively indicating that the deflection of large size tire shreds (300 mm) is about 2.5 percent higher than small size tire shreds (150 mm). The direct labour and material costs for large size tire shreds were \$12 per ton compared to \$30-\$65 per ton for small size tire shreds (Graham et al, 2001), suggesting that the large size tire shreds can be a feasible economical alternative compared to small size tire shreds. Previous research performed on the stress-strain response of small size tire shreds is summarized in Fig 5.9.

The elastic moduli of the three sizes of the tire shreds were estimated from the laboratory deflection tests and are shown in Figure 5.10 which shows that the resilient modulus of tire shreds increase with increase in bulk density of the shreds (Shalaby and Khan, 2002a). Previously, little research work has been reported on the resilience response of the tire shreds. Bosscher and Edil (1995) tested mixture of tire shreds and soil and reported that pure tire shreds were difficult to test due to the excessive displacement of the shreds however the resilient moduli of the 75 mm size pure tire shreds was found out by correlating it with the Poison ratio, Fig 5.11.

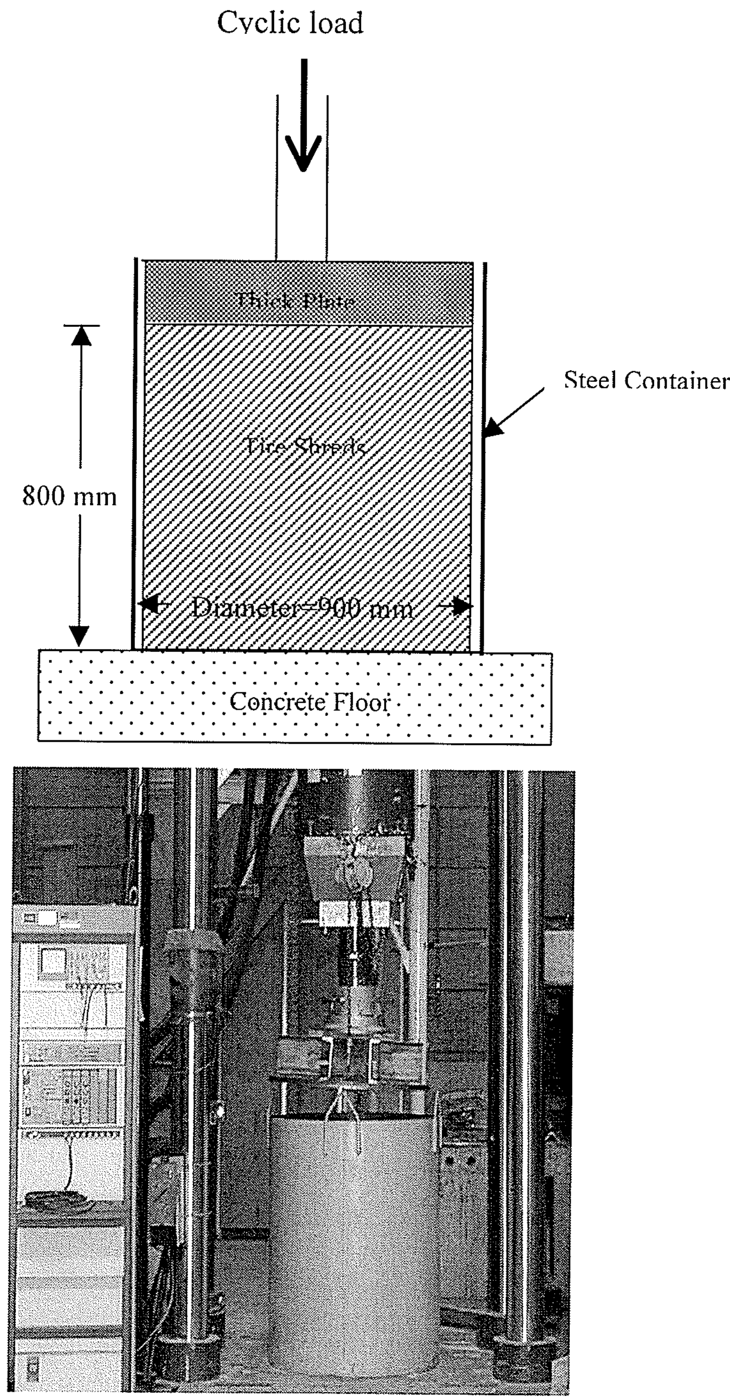


Figure 5.4 Laboratory compressibility test setup

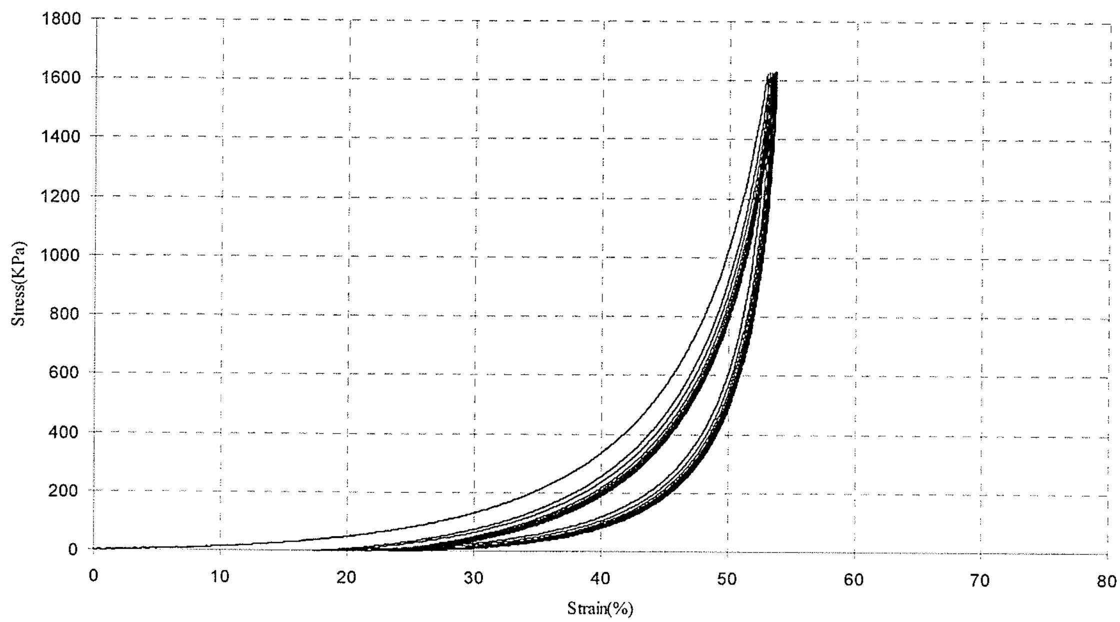


Figure 5.5 Stress-strain curves for 50 mm tire shreds

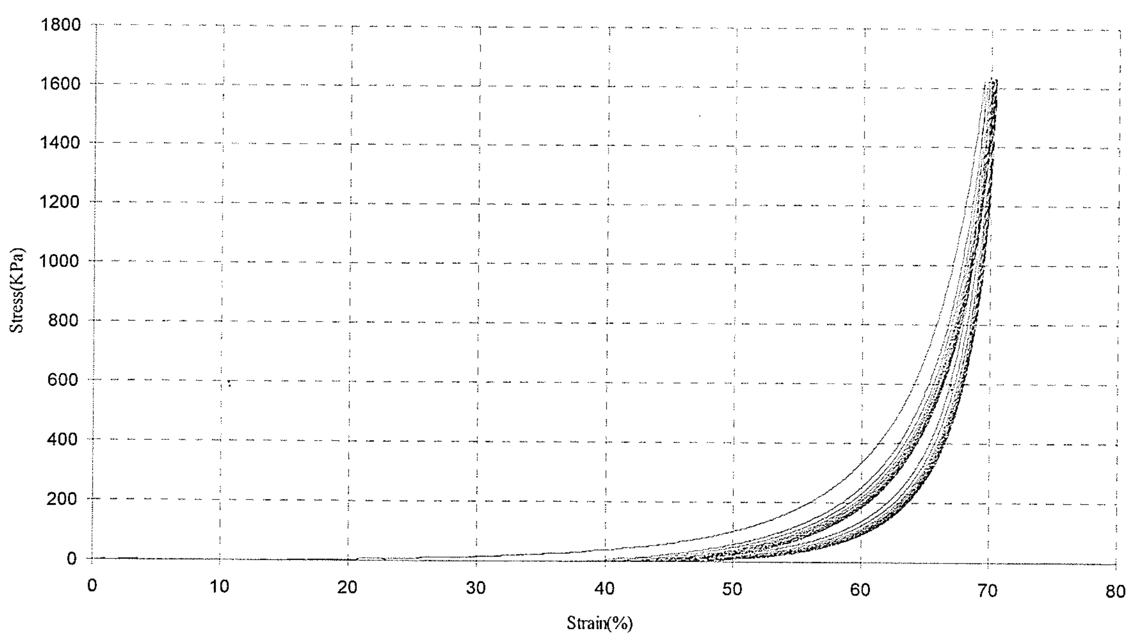


Figure 5.6 Stress-strain curves for 150 mm tire shreds

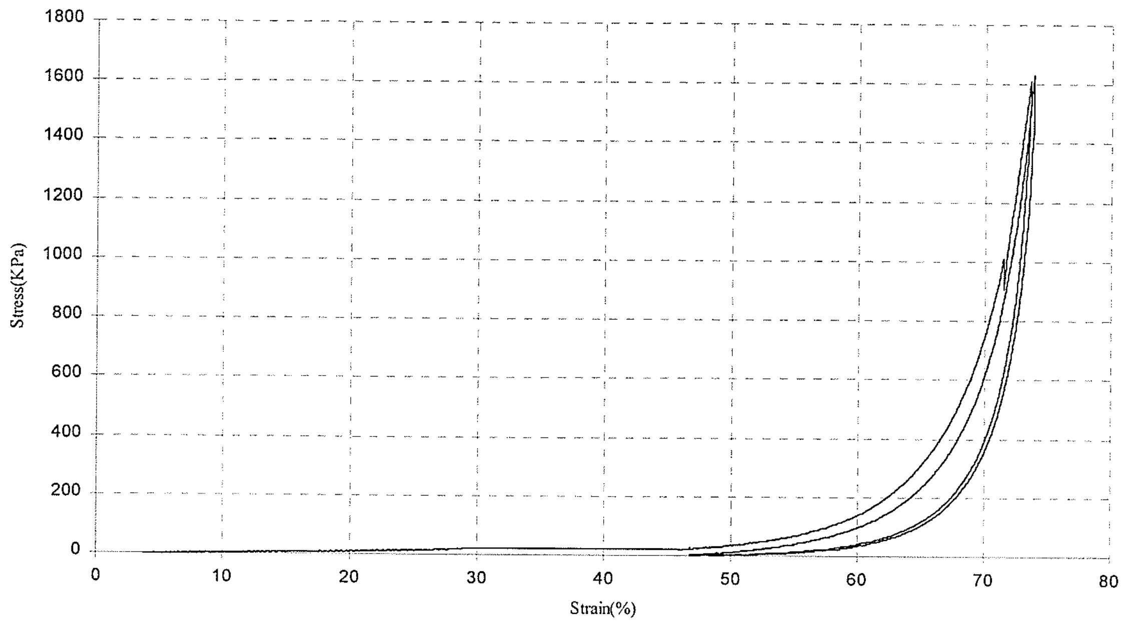


Figure 5.7 Stress-strain curves for 300 mm tire shreds

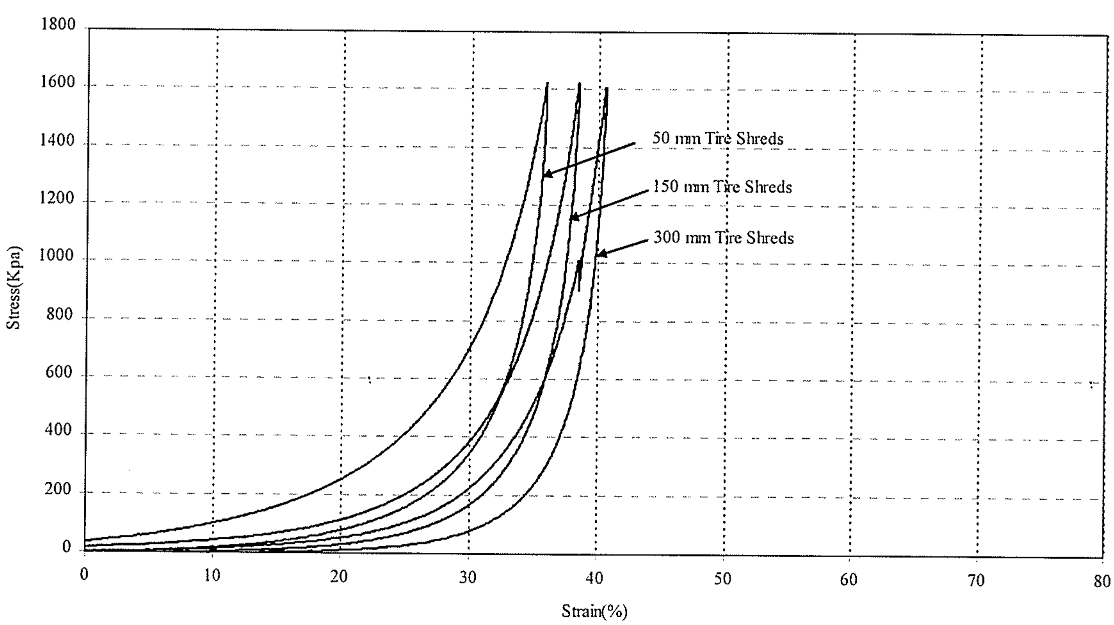


Figure 5.8 Constrained stress-strain responses of three sizes of tire shreds

Curve	Reference	Maximum size of tire shred (mm)	Size of testing mold
1	Edil and Bosscher, 1992	75	Diameter=152 mm Height=305 mm
2	Humphrey and Sandford, 1993	100	Diameter=305 mm Height=318 mm
3	Hsieh and Wu, 2000	75	300 x 300 mm

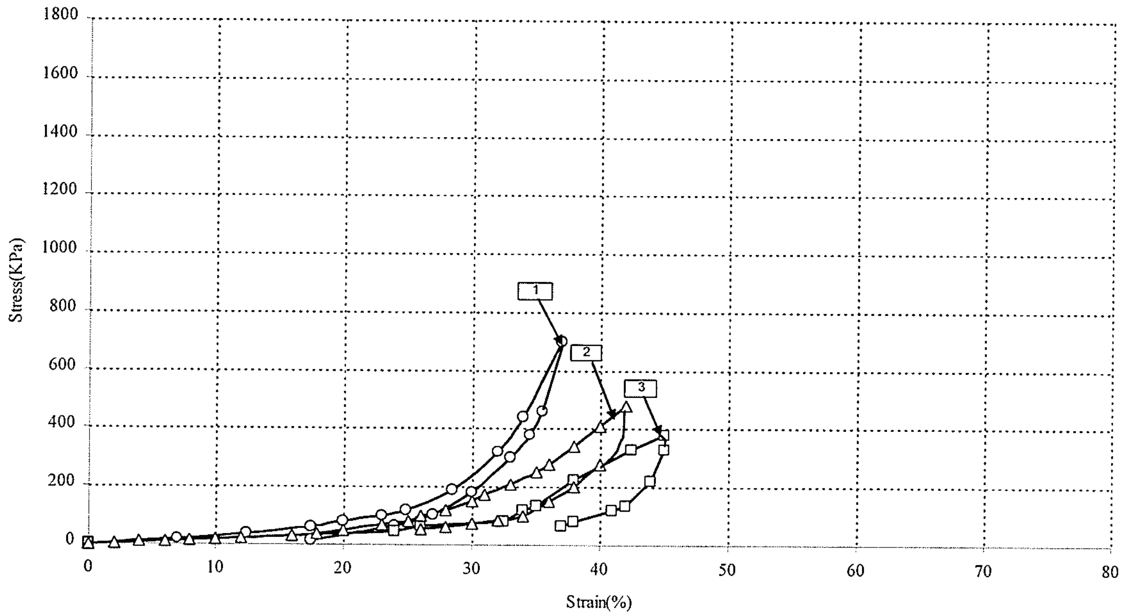


Figure 5.9 Stress-strain response of small size tire shreds from literature

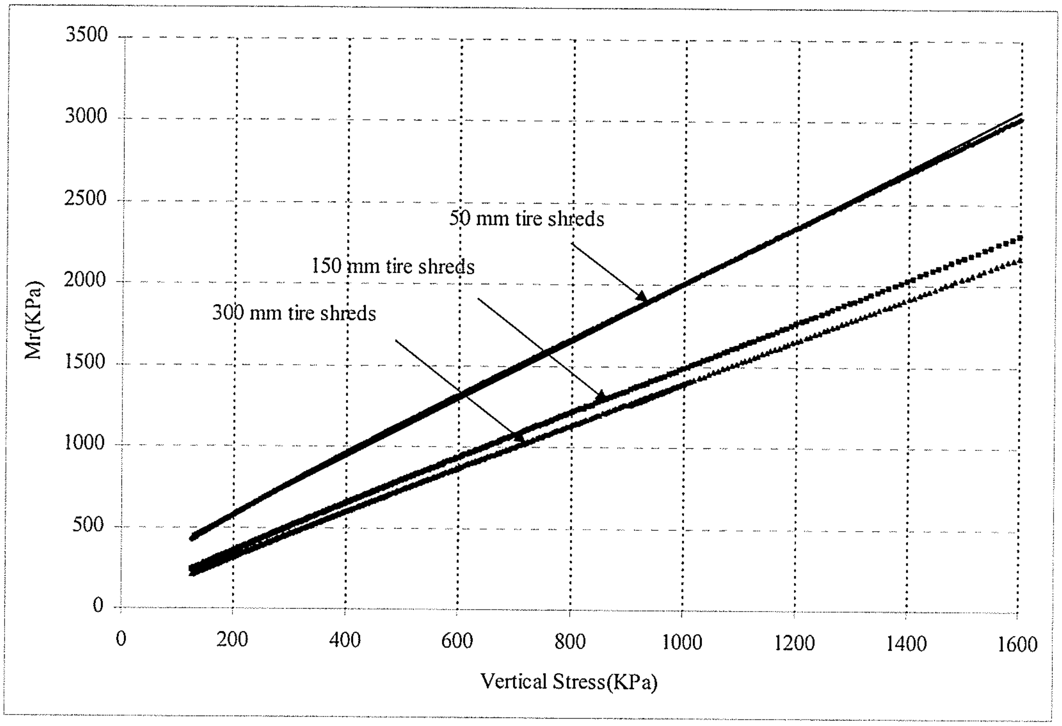


Figure 5.10 Resilience response of three sizes of tire shreds obtained from laboratory testing

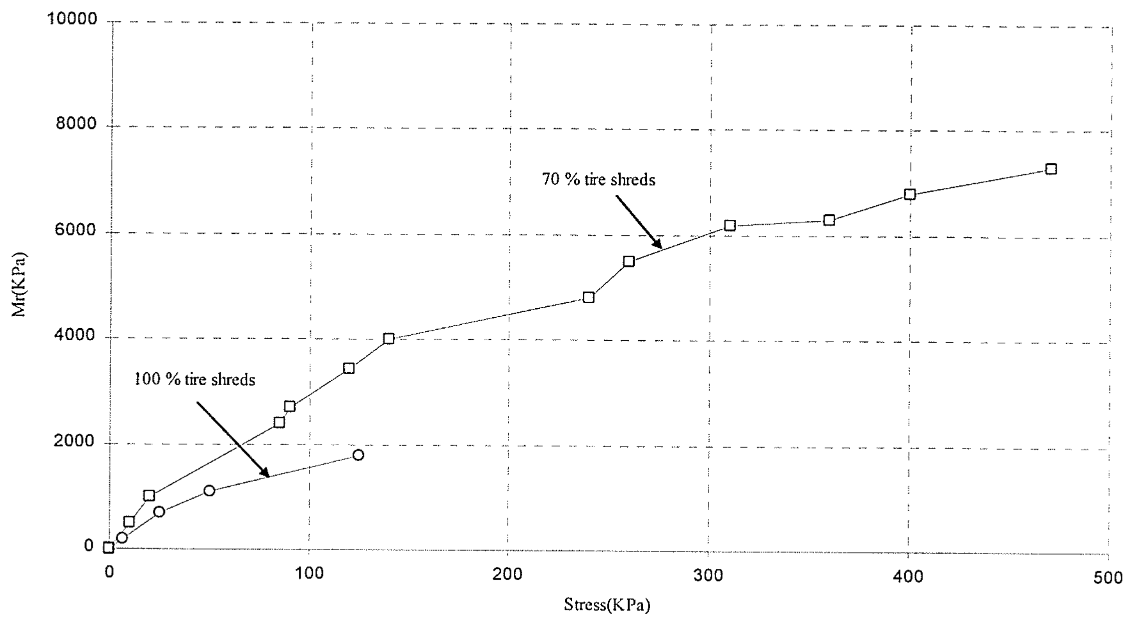


Figure 5.11 Resilience response of 75 mm size tire shreds

(Edil and Bosscher, 1995)

5.4 Deflection Analysis

KENLAYER is flexible pavement design software and is applicable to a multilayered system under stationary or moving wheel loads (Huang, 1993). This software was used to model the deflection of the tire shred embankment based on the laboratory test data. The elastic input parameters for the program are shown in Table 5.1. Construction equipment used for field compaction can exert a contact normal pressure of 35 kPa for wide-track bulldozer (Humphrey, 1996) and 56.5 kPa for crawler type tractor (Hager et al, 1998). A total of 704 kPa stress level, sum of field compaction stress and tire contact pressure of 695 kPa and a gravel surcharge stress of 8.82 kPa, was assumed for this analysis. Most of the deflections observed in the laboratory and field deflection tests were recoverable under the repeated applications of loads and only minor irrecoverable deflections were observed. Therefore tire shreds exhibit non-linear elastic behaviour after few initial cycles of load application (Edil and Bosscher, 1992). Linear and non-linear deflection analysis of the tire shred embankment was performed using a seven-layer elastic isotropic system as shown in Fig 5.12.

5.4.1 Layered Elastic Analysis

The approach for the deflection prediction of tire shred embankments used in this analysis is based on the application of elastic layer theory in which the road structure is characterized as a multilayered elastic system. In this analysis the subgrade was assumed to be infinite in horizontal and semi infinite in vertical direction while the other layers of the road embankment were assumed to have infinite extent in horizontal directions only. Load is expressed as a tire contact pressure, field compaction stress, exerted by construction machinery in the field, and gravel surcharge on top of the tire layer in the tire shred embankment. The determination of the required deflection is based on the effective resilient modulus values obtained from laboratory tests data.

5.4.1.1 Linear Elastic Analysis

In this analysis the embankment was assumed to be a linear homogenous mass having an elastic modulus, E, of the tire shreds independent of the level of stress and constant for all five layers of the tire shreds. It is possible to select approximate elastic moduli for the three sizes of the tire shreds from Fig 5.10 commensurate with the 704 kPa stress level.

5.4.1.2 Non-Linear Elastic Analysis

In non-linear analysis it can be assumed that the elastic modulus of each layer of the tire shreds is stress-dependent, Figure 5.10. The vertical stress due to the surface loading at mid-depth of each layer beneath the surface of the road was determined by the following equation (Huang, 1993).

$$\sigma_z = q\left(1 - \frac{z^3}{\left(a^2 + z^2\right)^{1.5}}\right) \tag{5.1}$$

Where σ_z = vertical stress at a depth z from an equivalent circular loaded area

q = uniform applied pressure on a loaded circular area

z = depth beneath the road surface

a = radius of the loaded area

The uniform normal pressure can be obtained by

$$q = \frac{P}{A} \tag{5.2}$$

Where P = applied surface load

A = loaded area

The surcharge stress of material, Q, is given by

$$Q_i = \sum \gamma_i h_i \tag{5.3}$$

Where γ = unit weight of material

h= thickness

The total vertical stress at a depth z of the tire shred embankment, σ_{tz}, can be given by

$$\sigma_{tz} = \sigma_z + Q \tag{5.4}$$

The vertical stresses for the elastic tire shreds layers of the road were obtained using equation 5.4 for the three sizes of tire shreds. The surface deflections were calculated by KENLAYER using the elastic moduli of the tire shreds obtained from Fig 5.10 for the respective stress levels. Coefficient of earth pressure at rest for the tire shreds was assumed to be 0.4 (Humphrey and Sandford, 1993) as an input parameter in KENLAYER for the non-linear elastic analysis.

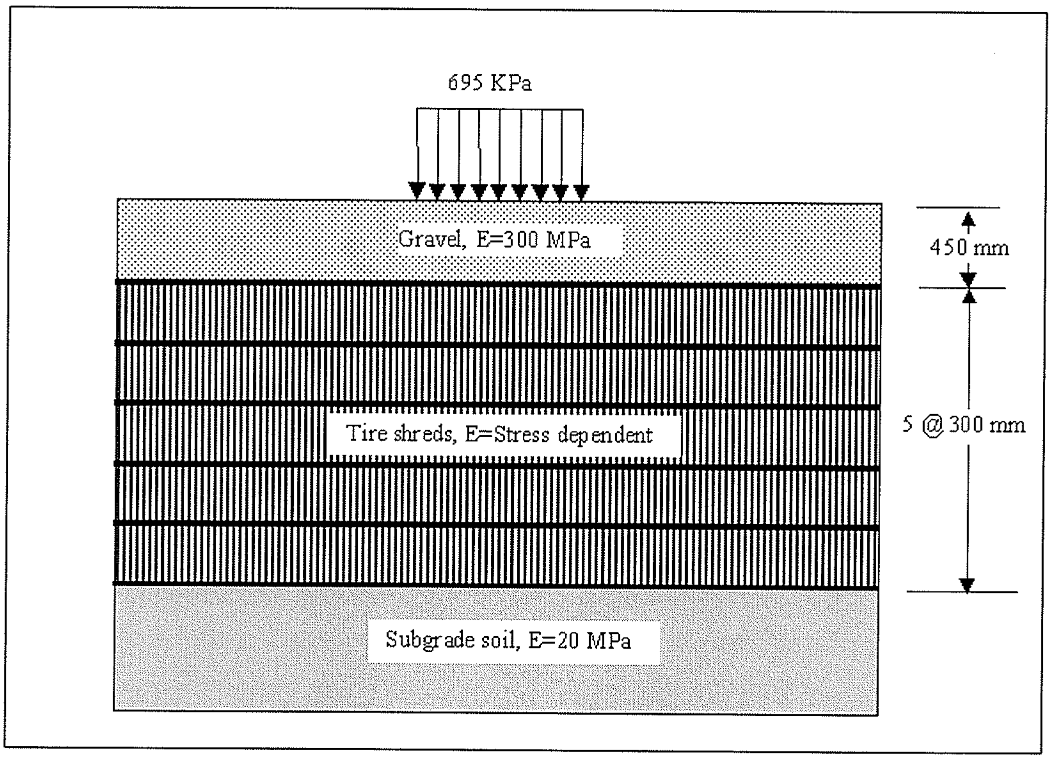


Figure 5.12 Tire shred embankment as a seven-layer elastic isotropic system

5.4.1.3 Results of Layered Analysis

The results of deflection analysis are presented in Table 5.2. Deflections of the tire shred road embankment are primarily controlled by the elastic moduli of the tire shreds .The integrity of the embankment depends on the resilient properties of the shreds. It is observed that the primary variables that influence the resilient response of tire shreds are applied stress and the compaction of the tire shreds. It is evident that the deflections of the road based on linear elastic analysis are approximately 40 percent smaller than when the fill is analyzed as non-linear elastic system, Fig 5.13. This means that the non-linear assumption in deflection prediction, based on material properties determined from a one-dimensional constrained compression test, gave a conservative estimate of the deflection of the tire shred embankment compared to the linear elastic assumption (Shalaby and Khan, 2002a). However it should be stressed that this conclusion is derived from analyzing limited combination of elastic input parameters and a simplified model of layered materials. Also it should be stressed that in situations where higher level of accuracy is required, elasto-plastic analysis may be performed.

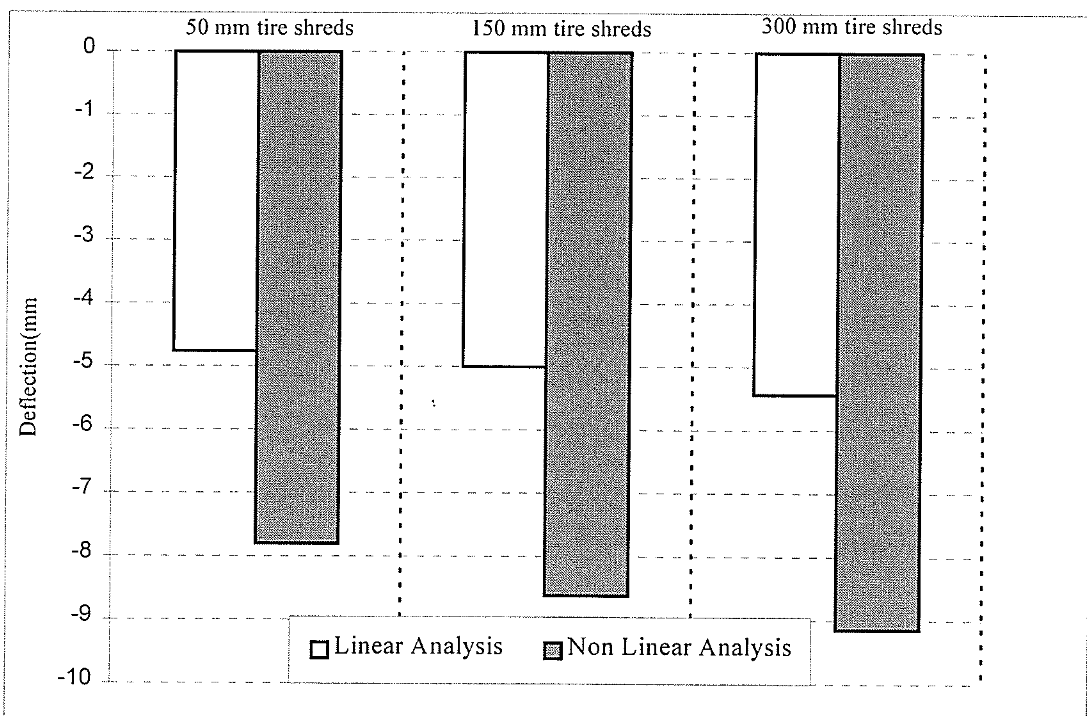


Figure 5.13 Predicted deflections from linear elastic and non-linear elastic analysis

Table 5.1 Input parameters for elastic analysis

Material	Layer thickness (mm)	Approximate stiffness modulus (kPa)	Poisson ratio	Unit weight (kg/m^3)
Gravel	450	300,000	0.30	2000
Tire shred	300	Stiffness modulus vs. vertical stress response is obtained from Fig. 5.10	0.30	533 for 50 mm size[1] 354 for 150 mm size[1] 342 for 300 mm size[1]
Subgrade soil	Infinite	20,684 [2]	0.40	1500

1. Uncompacted unit weights, 2. Estimated from M_r in Psi=1500 CBR (Huang, 1993).

Table 5.2 Surface deflections using KENLAYER

Nominal size of the tire shreds (mm)	Depth from surface (mm)	Vertical stress [1] (kPa)	Stiffness modulus [2] (kPa)		Surface deflection (mm)	
			Non-linear elastic analysis	Linear elastic analysis [3]	Non-linear elastic analysis	Linear elastic analysis
50	600	69.50	175	1400	7.80	4.76
	900	37.84	110			
	1200	27.39	75			
	1500	23.26	50			
	1800	21.72	35			
150	600	69.24	125	1200	8.61	5.00
	900	37.31	75			
	1200	26.33	65			
	1500	21.67	45			
	1800	19.60	30			
300	600	69.22	122	1000	9.14	5.43
	900	37.27	71			
	1200	26.25	62			
	1500	21.55	42			
	1800	19.44	21			

1. Theoretical values obtained from layered analysis using equation 5.4.
2. from stiffness modulus vs. vertical stress response using Fig 5.10.
3. Considering construction machinery compaction stress, tire contact pressure and surcharge at top of the tire layer of the tire shred embankment.

5.4.2 Deflection Prediction Model

Compressibility prediction is an important parameter in performance modeling and design of tire shreds embankments. Available literature provides very limited quantitative information on the mechanical behaviour especially on the compressibility characteristics of tire shreds and an equation for compressibility prediction of the tire shred embankments has not been defined. Development of compression parameters can help establish a model to predict the compressibility of the tire shreds. In the past compression parameters were developed for whole tires (Garga and O'Shaughnessy, 2000). The in-situ tests can provide more accurate and reliable results than laboratory tests in assessing compressibility behaviour and performance of the tire shreds. One-dimensional compression tests are commonly used in settlement estimation in geotechnical practice. One-dimensional constrained compression tests performed in the laboratory were used to determine the compressibility of the tire shreds using the following simple equation.

$$\delta = \lambda H \sigma_z \tag{5.5}$$

Where

δ =Compressibility of tires shreds (m)

λ =Coefficient of tire compressibility (m^2/kN)

H =Thickness of tire shred layer (m)

σ_z =Stress at depth z of tire layer (kN/ m^2)

The stress at the mid of tire shreds layer was obtained using the Boussineq's equation for distributed loads, equation 5.1 (Huang, 1993).

The one-dimensional coefficient of tire compressibility, λ, was obtained from the stress vs. compressibility response of tire shreds, Figure 5.14, using the following equation.

$$\lambda = \frac{1}{h_1}\left[\frac{(h_1 - h_2)}{(\sigma_2 - \sigma_1)}\right] \tag{5.6}$$

Where

h_1= thickness of tire shreds at stress level σ_1= 50 kPa

h_2= thickness of tire shreds at stress level σ_2= 100 kPa

The stress levels σ_1 and σ_2 in equation 5.6 were selected based on the actual conditions in the field during the field compressibility measurement. Stress level σ_1 represents the cumulative overburden and construction machinery stress at top of tire shred layer while stress level σ_2 is the sum of overburden pressure and equivalent stress for tire pressure of 550 kPa, equation 5.6. Coefficient of tire compressibility was found to be 0.0011, 0.0019 and 0.0022 m^2/kN for 50, 150 and 300 mm tire shreds respectively

To properly define an equation of tire compressibility, the parameters in equation 5.5 are defined to quantify the variation of compression characteristics of tire shreds, the thickness of road structure and the compaction pressure applied to the road. The compressibility of the three sizes of tire shreds, obtained from this equation is shown in Table 5.3, which shows that the equation reasonably captured the field compression response of the tire shreds and has good agreement with 25 mm of compressibility obtained in the field. The key variable affecting the design of the tire shred embankments is the compression behaviour of the tire shreds. Using these compressibility coefficients as a tool to predict the field performance, the settlement of shredded tire road embankments can be satisfactorily predicted and a reasonable design of shredded tire road embankments can be achieved.

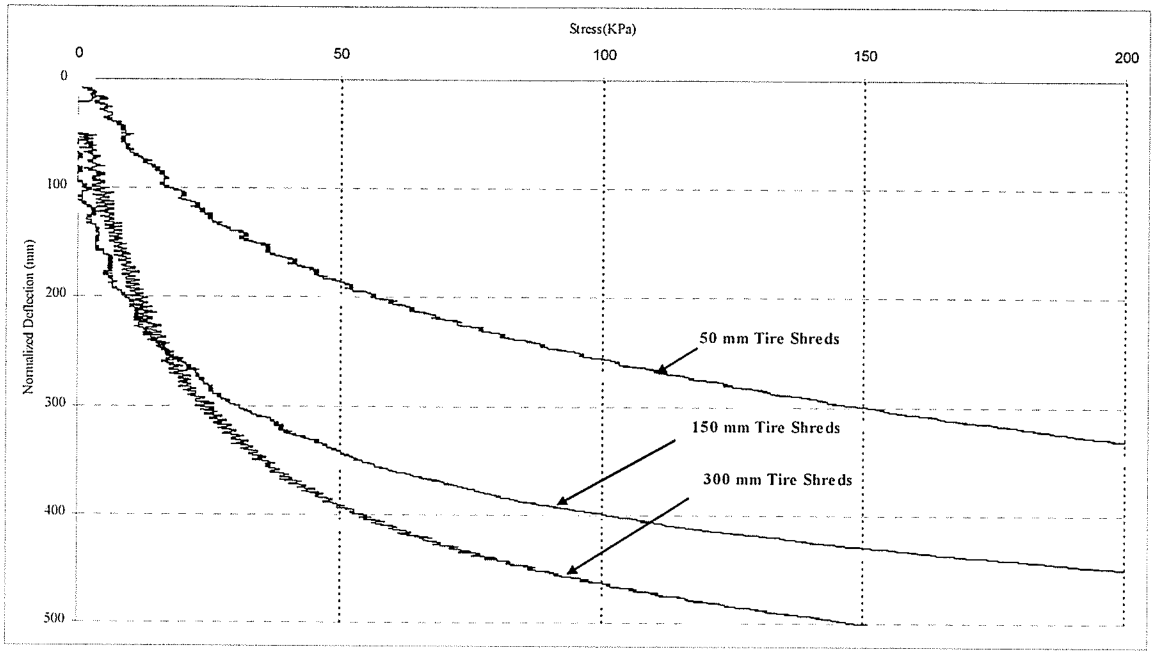


Figure 5.14 Laboratory stress vs. deflection response of three sizes of tire shreds

Table 5.3 Predicted deflections of tire shred embankment

Size of tire shreds (mm)	Coefficient of tire compressibility[1] λ (m^2/kN)	Stress at mid of tire shred layer corresponding to 550 kPa tire pressure [2] σ_z (kPa)	Deflection[3] δ (mm)
50	0.0011	12	19.8
150	0.0019	12	34.2
300	0.0022	12	39.6

1 Stress vs deflection response, equation 5.5
2 Boussineq's layered theory, equation 5.1
3 One-dimensional consolidation settlement, equation 5.6

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Waste tires have proved to be an ecological and financial burden in many regions of the world. In Canada, an equivalent of one waste tire per capita is added to the stockpiles annually. There are several applications for waste tires in road construction including lightweight embankments, crossing soft subgrade soils, pavement frost barriers, retaining walls and bridge abutment backfill, and as a drainage layer for edge drains. Road construction can utilize a large quantity of scrap tires however there is a shortage of technical data on design and performance. Given this lack of technical data, a gravel-surfaced lightweight road embankment was constructed in Manitoba on a soft ground using large size (300 mm) tire shreds in the base layer. The objectives were to monitor the performance of the road, examine the thermal and mechanical behaviour of the tire shreds and develop design guidelines for the construction of roads using tire shreds in the base layer. Performance of the road embankment was evaluated by a field monitoring program. The thermal behaviour of tire shreds was established from automated temperature measurements. Deflection of the tire shred embankment was computed using 21,000 kg tandem axle load. The effect of tires shreds on the water quality was determined by conducting organic and inorganic water quality testing on samples of groundwater collected from site.

In the past tire shreds have been used on trial basis in road embankments as a lightweight fill. Little is known about the engineering properties of tire shreds. There are also no set design standards for road construction using tire shreds as a base layer. An effort has been made in this research project to study the field response of tire shreds by constructing a test embankment and establishing design guidelines for roads construction using tire shreds in the base layer. In North America the direct labour and material costs for large size and small size tire shreds are \$12 and \$30-\$65 per ton respectively. In Vermont the tire chips at the cost of \$1 per cubic yard proved to be an economical option compared to gravel having cost of \$3.85 per cubic yard. However in the province of Manitoba, the costs for the tire shreds are not fully established yet, as the market of tire recycling is in the developing stage.

In this thesis the construction, instrumentation and performance-monitoring program of a full-scale tire shreds test road embankment is described. This embankment was constructed on poor subgrade soil in Manitoba. Deflection prediction models, based on laboratory and field compressibility testing, are developed for the design of tire shred embankments. Following are the conclusions made.

1. The steady state thermal gradient in tires, clay and gravel is approximately 10 °C /m, 2 °C /m and 1.5 °C /m respectively.
2. The thermal conductivity of the tire shreds with an approximate dry density of 500 kg/m^3 is five times lower than the thermal conductivity of clay with a dry density of 1500 and moisture content of 25 percent.
3. Frost penetration in the tire shred embankment is larger than in the natural ground because of the low water content and presence of large voids in tire shreds and the difference in snow cover.
4. The observed surface deflection of the tire shred embankment is 15 to 25 mm, under 21000 kg tandem axle load. An average rebound of 11 mm and irrecoverable displacement of 7 mm were recorded after two passes of load.
5. The elastic modulus of the tire shreds is proportional to the bulk density and nominal size of the shreds.
6. Non-linear elastic isotropic analysis gives a conservative estimate of the deflection of the tire shred embankments compared to the linear elastic analysis.

The design of road embankments with large-size tire shred layers can be made using the non-linear elastic analysis model presented in this thesis.

7. Large size tire shreds can be an economical alternative compared to the small size tire shreds in the construction of the tire shred embankments.
8. Compression parameters of tire shreds can be reasonably determined from one-dimensional constrained compression tests in the laboratory.
9. Coefficient of tire compressibility for 50, 150 and 300 mm tire shreds is found to be approximately 1.1, 1.9 and 2.2 m^2/MN respectively.
10. The compressibility of tire shreds road embankments can be satisfactorily interpreted using the simple equation presented in the thesis.

6.2 Recommendations

Following recommendations for the design of road embankments using tire shreds in the base layer can be made from this research

- *Thickness of a Tire Shred Embankment*

Limiting the frost depth into the subgrade soil limits the potential for frost penetration and thaw weakening. One of the implications of the preceding calculation of depth of frost penetration is that the total depth of road structure in the frost-affected areas can be calculated by these results. Most state highway agencies in the United States use an empirical rule of thumb that the total pavement structure should be at least 50 percent of the expected depth of frost penetration in frost-affected areas (WSDOT, 1995). The depth of frost penetration obtained in this study can be used in the design of tire shred embankments in frost affected areas by taking the total thickness of pavement structure as half of the expected depth of frost penetration, 625 mm. This minimum thickness of pavement structure can give more accurate analysis results for analogous conditions encountered during this monitoring program.

- *Deflections and Resilient Response Prediction Model*

Conventional road design procedure based on layered analysis requires the assessment of elastic moduli of each material in a road structure. The design of tire shred embankments can be characterized by the resilient moduli of tire shreds. However due to the complexity of the shape of tire shreds and equipment requirement, it is desirable to develop an approximate method for the estimation of resilient modulus of the tire shreds and deflection prediction of the tire shred embankment.

A non-linear layered elastic isotropic model has been developed in this research to relate the resilient modulus of the tire shreds with the applied stress at the top of the embankment and to predict the deflections. This model was developed by studying the resilient and irrecoverable strain of three sizes of tire shreds under the load/unload cycles in the laboratory and field. The model provides an estimation of the resilient modulus of tire shreds and deflections of the tire shred embankment. Model provided good estimation of deflection of tire shred embankment compared with deflections obtained during field deflection test. Using this approximate procedure, deflections of the tire shred embankments can be predicted and a satisfactory road design can be achieved using large size tire shreds in the base layer.

- *Deflection Prediction using Deflection Equation*

Presently there is a lack of technical data on the compressibility characteristics of tire shreds that can lead to deflection prediction of the shreds. There is a need to predict the deflection behaviour of tire shreds using a simple equation. Compression behaviour of tire shreds is characterized in this research in terms of coefficient of tire compressibility. This coefficient of tire compressibility is easy to use and inexpensive to evaluate. It can lead to the assessment of the deflection response of the tire shreds and alternatively deflection of the embankments can be estimated using a simplified settlement equation. This equation can be used for preliminary estimate of the deflection response of tire shreds to various stress level.

Following are the recommendations for future research.

1. The tire shred embankment should be opened to the gravel hauling trucks and a long term field monitoring program undertaken to monitor the settlement of the tire shreds under moving loads.

2. Presently the visual compaction inspection of the tire shreds layer under compaction machinery is the common method for the field quality control. There is a need of a compaction measurement rational method to be developed and field tested. This method will help to produce a reliable field quality control process.

3. The water quality monitoring should remain continuous to get more information on the effects of tire shreds on the ground water quality.

4. Laboratory deflection response of the tire shreds under constant load needs to be investigated. Such deflection behaviour of tire shreds can be assessed by laboratory creep tests. Also in situations where higher level of accuracy is required elasto-plastic deflection analysis of the tire shred embankment may be performed and compared with elastic analysis.

5. Lightweight tire shred fills have the potential for consuming large quantities of scrap tires in a technically feasible manner. However economic analysis is a major factor that is used to determine the best use of discarded waste tires. The development of a profit-per-tire model can be a useful analysis tool for the construction of lightweight tire shreds embankments in future.

6. A control section of conventional road should be constructed adjacent to the tire shred embankment. Field monitoring program has to be undertaken to compare the field response of the large size tire shred embankment with a conventional road.

REFERENCES

Ahmed, I., Lovell, C.W. 1992. Use of Waste Materials In Highway Construction: State of the Practice and Evaluation of Selected Waste Products, Transportation Research Record No. 1345, Transportation Research Board, Washington, D.C.

American Society for Testing and Materials. 1998. ASTM, D 6270-98: Standard Practice for Use of Scrap Tires in Civil engineering Application, Annual Book of ASTM Standards, Volume 11.04, pp 501-520, American Society for Testing and Materials, Philadelphia.

Bosscher, P.J., Edil, T.B. 1995. Design of Highway Embankments Using Tire Chips, Environmental Geotechnics Report No.95-2, University of Wisconsin, Madison.

Bowles, J.E. 1992. Engineering Properties of Soils and Their Measurement, pp. 15 – 79, 201 – 211, McGraw Hill, Inc., Hightstown, New Jersey.

Canadian Council of Ministers of the Environment, CCME. 1999. Summary of existing Canadian Environmental Quality Guidelines (EQGs). CCME Publications, Winnipeg, Manitoba.

http://www.mbnet.mb.ca/ccme/pdfs/ ceqg_rcqe/summary_table_e.pdf. Accessed Nov 20, 2001.

Dickson, T., Dwyer, D., Humphrey, D. 2001. Prototype Tire Shred Embankment Construction by the New York State Department of Transportation, 80th Annual Meeting of the Transportation Research Board, Washington, D.C.

Department of Defense. 1966. Calculation Methods for Determination of Depths of Freeze and Thaw Soils-Emergency Construction, Department of the Air Force, Manual AFM 88-40, Chapter 46, Washington D.C.

Eaton, R.A., Roberts, R.J. and Humphrey, D.N. 1994. Gravel Road Test Sections Insulated with Scrap Tire Chips, Construction and First Year's Results, U.S Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.

Edil, T.B., Bosscher P.J. 1992. Development of Engineering Criteria for Shredded Waste Tires in Highway Applications, Final Report, Research Project No. WI 14-92, Wisconsin Department of Transportation, Division of Highways, Madison, WI.

Engstrom, G., Lamb, R. 1994. Using Shredded Waste Tires as a Lightweight Fill Material for Road Subgrades, Report No. MN/RD-94/10, Minnesota Department of Transportation, Physical Research and Geotechnical Engineering, Maplewood, MN.

United States Environmental Protection Agency. 1996. Drinking Water Standards, http://www.epa.gov/safewater/standards.html, Accessed on Nov 20, 2001.

Eyles, J., Sider, D., Baxter, J., Taylor S.M. and Willms D. (1990) The Impacts and Effects of the Hagersville Tire Fire: Preliminary Analysis and Findings, Proceedings, Technology Transfer Conference, Toronto: Environment Ontario, 818-829.

Farouki, O.T. 1986. Thermal Properties of Soils, Trans Tech Publications, D-3392 Clausthal-Zellerfeld, Germany.

Frascoia, R.I. 1993. Tire Chips in the Base Course of Local Road, Report No. 94-2, Vermont Agency of Transportation, Montpellier, Vermont.

Graham, M.A., Kjartanson, B.H., Lohnes, R.A. 2001. Shear Strength of Large Size Shredded Scrap Tires, 80th Annual Meeting, Transportation Research Board, Washington, D.C.

Highway Research Board. 1952. Frost Actions in Soil, A Symposium Special Report No. 2, Washington, D.C.

Hager, G., Dahill, B., Boundy, B., 1998. Construction and Instrumentation of a Shredded Tire Fill at the Double Nickel Land slide, Transportation Research Board, 77th Annual Meeting, Washington, D.C.

Hoel, L.A. and Garber, N.J. 1996. Traffic and Highway Engineering, pp. 817 – 845, PWS Publishing, Pacific Grove, California.

Hoppe, J.E. 1994. Field Study of a Shredded Tire Embankment, Virginia Transportation Research Council, Charlottesville, Virginia.

Hsieh, C.W. and Wu, J.H. 2000. Stabilization of a Vertical Chip Embankment with Geogrids, Transportation Research Board, 79th Annual Meeting, Washington, D.C.

Huang, Y. 1993. Pavement Analysis and Design, Prentice Hall, New Jersey.

Humphrey, D.N. and Sanford T.C. 1993. Tire Chips as Lightweight Subgrade Fill and Retaining Wall Backfill, Symposium Proceedings of Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities, Denver, Colorado.

Humphrey, D.N. and Nickels, W.L. 1994. Tire Chips as Subgrade Insulation and Lightweight Fill, 18th Annual Meeting of the Asphalt Recycling and Reclaiming Association, Pompano Beach, Florida.

Humphrey, D.N. 1996. Civil engineering Applications of Chipped Tires, pp 34, Manitoba Tire Stewardship Board, Winnipeg, Manitoba.

Humphrey, D.N. 1996. Investigation of Exothermic Reaction in Tire Shred Fill located on SR 100 in Ilwaco, Washington, report prepared for Federal Highway Administration, Washington, D.C.

Humphrey, D.N., Chen, L.H. and Eaton, R.A. 1997. Laboratory and Field Measurement of the Thermal Conductivity of Tire Chips for Use as Subgrade Insulation, 76th Annual Meeting, Transportation Research Board, Washington, D.C.

Humphrey, D.N., Whetten, N, Weaver, J., Recker, K., Cosgrove, T. 1998. Tire Shreds as Lightweight Fill for Embankments and Retaining Walls, Proceedings of Recycled Materials in Geotechnical Applications, American Society of Civil Engineers (ASCE), pp. 51-65.

Humphrey, D., Katz L., 2000. Five Year Field Study of the Water Quality Effects of Tire Shreds Placed Above the Water Table, Transportation Research Board, 79th Annual Meeting, Washington D.C.

Kersten, M.S. 1949. Thermal Properties of Soils, Engineering Experiment Station, Bulletin 28, University of Minnesota, MN.

Khan, R.A. and Shalaby, A. 2001. Recycling of Shredded Rubber Tires as Road Base in Manitoba: A Case Study. 54th Annual Canadian Geotechnical Conference, Calgary, Alberta.

Khan, R.A. and Shalaby, A. 2002. Performance of Road Base Constructed with Shredded Rubber Tires. 2002 CSCE Transportation Specialty Conference, Montreal, Quebec.

Klymchuk, K., Shalaby, A., Graham, J. 1999. A Geotechnical Report On The Construction of Gravel Road with Shredded Rubber Base Located at Lesters Cartage and Construction, 50 Garven Road, Winnipeg, Manitoba, Department of Civil engineering, University of Manitoba.

Lee, J.H, Salgado, R, Bernal, A and Lovell, C.W. 1999. Shredded Tires and Rubber-Sand as Lightweight Backfill, Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers (ASCE), Volume 125, issue 2, pp 132-141, Reston, VA.

Liu, H.S, Mead, J.L., and Stacer R.G. 1998. Environmental Impacts of Recycled Rubber in Lightweight Fill Applications, Chelsea Centre for Recycling and Economic Development, University of Massachusetts, Lowell.

National Cooperative Highway Research Program. 2001. Appropriate Use of Waste and Recycled Materials in Transportation Industry, Project 4-21, Transportation Research Board, Washington, D.C.

Read, J., Dodson. T. and Thomas. J. 1990. Use of Shredded Tires for Lightweight Fill, Report DTFH-71-90-501-OR-11, Oregon Department of Transpiration, OR.

Shalaby, A. and Khan, R.A. 2002a. Temperature Monitoring and Compressibility Measurement of a Tire Shred Embankment in Manitoba, Presented in 81st Annual Meeting of Transportation Research Board and accepted for publication in Journal of Transportation Research Record (TRR), National Research Council, Washington D.C.

Shalaby, A. and Khan, R.A. 2002b. Shredded Rubber Tires as a Lightweight Fill in Road Base Construction, Workshop proceedings, International Workshop on Lightweight Geo-material, Japanese Geotechnical Society, Tokyo, Japan.

Tian, P., Zaman, M.M., Laguros, J.G. 1998. Transportation Research Record No. 1619, Transportation Research Board, Washington, D.C.

Turner Fairbank Highway Research Centre. 2000. User Guidelines for Waste and By-product Materials in Pavement Construction, Federal Highway Administration (FHWA), http://www.Tfhrc.gov/hn20/recycle/waste/st1.htm, Accessed on Nov 20, 2001.

Tweddie, J.J., Humphrey, D.N. and Sanford T.C. 1998. Full Scale Field Trials of Tire Shreds as Lightweight Retaining Wall Backfill Under At-Rest Conditions, Transportation Research Record No. 1619, Transportation Research Board, Washington, D.C.

Winnipeg Sun. 2001. Tire Fire Started Accidentally Continues to Smoulder Just West Of Winnipeg. News Paper Article, April 16, 2001.

Wheaten, N., Weaver, J., Humphrey, D., and Sandford, T., 1997. Rubber Meets the Road in Maine. Civil Engineering, 67(9): 60-63.

Wright, P.H. and Paquette, R.J. 1987. Highway Engineering, John Wiley and Sons, New York, NY.

Washington State Department of Transportation. 1995. Pavement Guide, Olympia, WA.

APPENDICES

APPENDIX 1

TYPICAL BORE HOLE LOG

PROJECT: Tire Shred Embankment   BOREHOLE: Typical

Description and Classification	Sample Depth (m)	Sample No.
Topsoil - Dark brown to black, organics, fine sand	0.2	1
Medium grey-brown clay, roots silt lenses and nodules, fine sand	0.6	2
Firm grey clay, sandy, silt lenses, silt nodules, roots	1.2	3
Firm grey-brown clay, roots, oxides sand lenses (white), silt nodules	1.8	4
Dark grey clay, sand lenses, silt lenses, roots	2.4	5
	3.0	6

Depth (m): 0.2, 0.4, 0.6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4

Water Content: P.L. M.C. L.L. — 25 50 75

Shear Strength: 15 30 45 60 75

End of Hole @ 3.0 m

Comments: The borehole was started at the elevation that the tires will be placed. No compaction or excavation will take place prior to construction. The moisture contents were collected for each sample. The L.L. and P.L. are the results from the combined samples

APPENDIX 2

Table 1. Moisture content determination

Borehole	Sample No.	Depth of Sample (m)	Moisture Content, %	Soil Mixture
1	1	0.2	66.1	-
	2	0.8	44.9	-
	3	1.4	33.8	Type A
	4	1.8	34.1	Type B
	5	2.4	29.8	Type B
	6	3.0	51.2	-
2	1	0.8	37.5	Type A
	2	1.2	35.6	Type C
	3	1.8	38.1	-
	4	2.4	38.0	Type B
3	1	1.0	35.8	Type A
	2	1.7	31.7	Type C
	3	2.4	31.2	Type B
4	1	0.2	42.8	-
	2	0.6	40.9	Type A
	3	1.2	33.7	Type C
	4	1.8	34.3	Type B
	5	2.4	34.8	-
	6	3.0	39.7	-

APPENDIX 2

Table 2. Soil fractions

Soil Mixture	Type A	Type B	Type C
Clay (%)	61.0	46.0	48.0
Silt (%)	35.1	43.0	45.4
Sand (%)	3.9	11.0	6.6

Table 3. Atterberg's limits

Soil Mixture	Type A	Type B	Type C
Liquid Limit (%)	68.5	52.0	59.9
Plastic Limit (%)	23.0	19.2	21.4
Plasticity Index (%)	45.5	32.8	38.4

Table 4. AASHTO soil classification

Soil Mixture	Type A	Type B	Type C
Classification	A – 7 – 5 (50)	A – 7 – 5 (31)	A – 7 – 6 (40)
Soil Description	Medium gray-brown clay, silt, sand.	Medium -firm gray-brown clay, silt nodules and lenses, sand lenses.	Medium-firm gray clay, traces of sand and silt.

Note: The number in parentheses represents the Group Index.