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Research

Development of Design Guidelines for Use of Shredded Tires as a Lightweight Fill in Road Subgrade and Retaining Walls

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The use of shredded tires as a lightweight fill material over weak soil deposits is gaining popularity as a means of disposing a great quantity of an undesirable waste material in a beneficial manner. This report discusses the production, past applications, and properties of shredded tires with respect to their use in lightweight fills.

Shredded tires have the advantages of low bulk density, high permeability, and insensitivity to the presence or state of moisture. However, they possess a high degree of compressibility, and they exhibit a degree of rebound atypical of materials normally used in lightweight fills (e.g., woodchips). Before using shredded tires in a fill, one must consider the layer thickness of the shredded tires, the amount of overburden to be placed on the tires, the type of pavement surface, and the volume of heavy traffic expected to use the roadway.

Because of the orientation of shredded tires after placement, the importance of anisotropy as a future research topic is discussed.

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DEVELOPMENT OF DESIGN GUIDELINES FOR USE OF SHREDDED TIRES AS A LIGHTWEIGHT FILL IN ROAD SUBGRADE AND RETAINING WALLS

FINAL REPORT

prepared by

Andrew Drescher
David Newcomb

Department of Civil and Mineral Engineering
University of Minnesota

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Submitted to

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building, 117 University Avenue
St.Paul, MN 55155

EXECUTIVE SUMMARY

It is estimated that approximately 240 million automobile and truck tires are discarded annually in the U.S. Until recently, these have typically been disposed of in landfills and in tire stockpile sites where they pose potential safety and health problems as well as being aesthetically offending. The latest use of shredded tires as lightweight fill material is encouraging, however, and the number of applications may grow, providing their engineering properties become more understandable and the quantifying parameters are known. This report summarizes exploratory field and laboratory tests for determining the basic properties of shredded tires.

In the field tests, where large-size shreds were used, the effort necessary for compacting layers of shredded tires with a dozer was measured. In the laboratory tests, the compressibility of small-size shreds was investigated by means of an one-dimensional compression test. In addition, for both the large- and small-size shreds, their gradation, bulk density, porosity and void ratio were determined. For comparison, wood chips were tested also.

The results show that the bulk density of shredded tires is between that of traditional granular fill material and wood chips. However, their compressibility and rebound are much higher than that of the latter material, which could lead to premature fatigue failure of hard surface pavements. The apparent anisotropy of a shredded tire mass may also cause errors in predicting pavement deflections by means of classical, elastic multilayer system analysis which assumes material anisotropy.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

Figure | Page

Figure | Page

LIST OF TABLES

CHAPTER 1

INTRODUCTION

BACKGROUND

Over the past twenty years there has been a growing concern regarding the volume of waste products requiring disposal, and the depletion of natural resources. For instance, it is estimated that more than 200 million automobile tires and 40 million truck tires are discarded each year in the United States [1]. This represents about 2.1 million tons of scrap passenger tires and roughly 1.9 million tons of scrap truck tires [1]. The state of Minnesota alone generates 3 million tires. The magnitude of this problem has prompted the study of ways to utilize used tires which has resulted in a number of available technologies.

Discarded tires, in their original or shredded form, have been used for numerous purposes, such as road subgrade, rubberized asphalt, artificial reefs, breakwaters, retaining wall back-fill, and as a source of energy. The availibility of discarded tires makes this waste product extremely attractive as an alternative lightweight construction material, and as a fuel supply with a heat value of approximately 14,000 BTU/lb; the latter use is frequently viewed as a solution to a disposal problem rather than as a major source of energy.

OBJECTIVE

The objective of this research was to identify one or more suitable methods for the utilization of shredded tires in road subgrades and as backfill in retaining walls. Emphasis was placed on investigating the physical and mechanical parameters of the shredded tires such as size, bulk unit weight, specific gravity, porosity, angle of repose, and compressibility coefficients. These parameters are used in the design of highways or in geotechnical construction.

SCOPE

This study consisted of three phases. The first phase was a technology review consisting of an investigation of the available literature and a summary of shredded tire use as a lightweight fill in Minnesota. The second phase of the research entailed monitoring the behavior of shredded tires during the construction of a roadway. In the third phase, laboratory experiments were performed on the tire fill material and the results were compared to those obtained from woodchips, a conventional lightweight fill material.

CHAPTER 2

THE NATURE OF RUBBER TIRES

The tires characteristics are presented in this chapter. It contains two sections. The first deals with the categories of tires and the second presents the types of tires available.

The tire market is complex, with a complicated network of interactions. While the new tire market is dominated by a few firms (16 firms produce new U.S tires, and the five-firm concentration ratio is 76%), the retreading and disposal markets are much more widely dispersed, including service stations, specialized disposal companies, individuals, and others. The market structure affects the incentives of each of these interactions, and changes in the incentives can greatly infuence the recovery of resources from discarded tires.

There are three physical tire constituents: *fabric, bead wire,* and *rubber compound*. Tables 1 and 2 [2] show the tire constituents by weight and rubber compound content, respectively. The principal chemical constituents of tires are *carbon* (83%), *hydrogen* (7%), and small quantities of *nitrogen*, *oxygen*, and *sulfur*.

CATEGORIES OF TIRES

There are four major categories of tires used in this country: *passenger*, *truck*, *farm*, and *off-road*. Figure 1 [3] illustrates the distribution of the annual total of over 225 million new tires among each of these groups. Farm and off-road tires, which make up only 3% of the market, are very specialized and contribute little to the overall scrap tire problem.

Passenger tires come in rim sizes of 12 to 15 inches and weigh anywhere from 15 to 30 pounds, with a generally accepted average of about 22 lbs. Truck tires come in rim sizes of 15 and 16 inches for lightweight vehicles, and 15 to 24 inches for heavy vehicles. Lightweight-duty truck tires weigh 30 to 60 lbs, while for heavy-duty tires the range is 90 to 200 lbs.

Table 1. Tire Constituents by weight (lbs) [2].

Tire Constituents	Weight
Fabric	2.5
Bead Wire	1.0
Rubber Compound	21.5
TOTAL	25.0

Table 2. Rubber compound content [2].

Material	% of Total	Weight in lbs
Rubber Polymer (including reclaim)	47	10.1
Carbon Black	30	6.5
Oil	18	3.9
Chemicals	3	0.6
Zinc Oxide	2	0.4
TOTAL	100	21.5

TYPES OF TIRES

There are basically three types of passenger tires currently being produced: *bias-ply, bias-belted,* and *radial* tires; while truck tires generally have either a bias or radial configuration. Figure 2 [3] shows the distribution of the annual total of over 225 million new tires among each of these types. Tables 3 and 4 show the percentage of the reinforcement materials in the cord and belting, respectively.

Structural characteristics affect wear, insofar as some types of tires run considerably cooler than others. Radial tires, which are subject to much less flexing than the other types, are expected to give better mileage than bias-ply and bias-belted tires, at least for some cars.

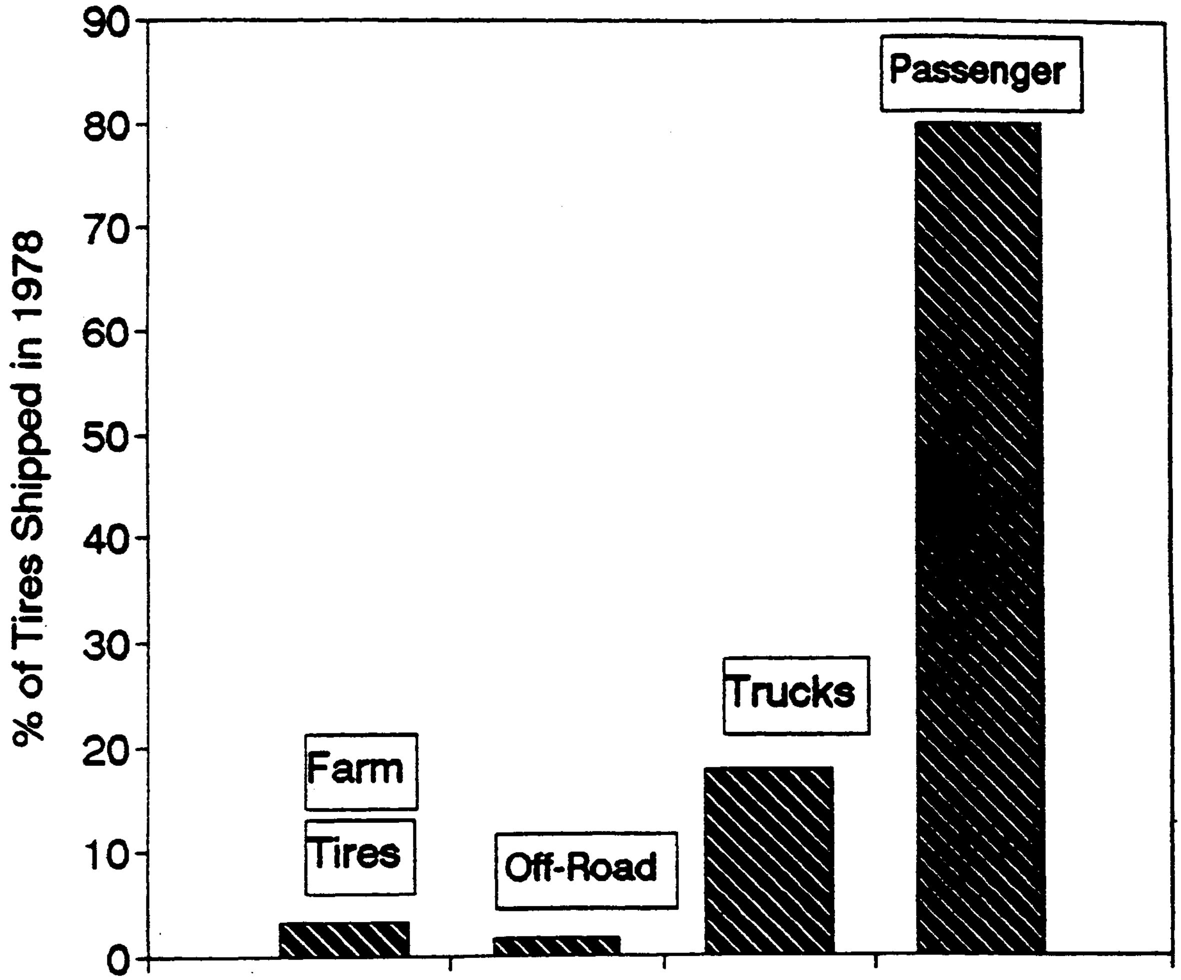


Fig. 1. Distribution of annual total tires by each category [3].

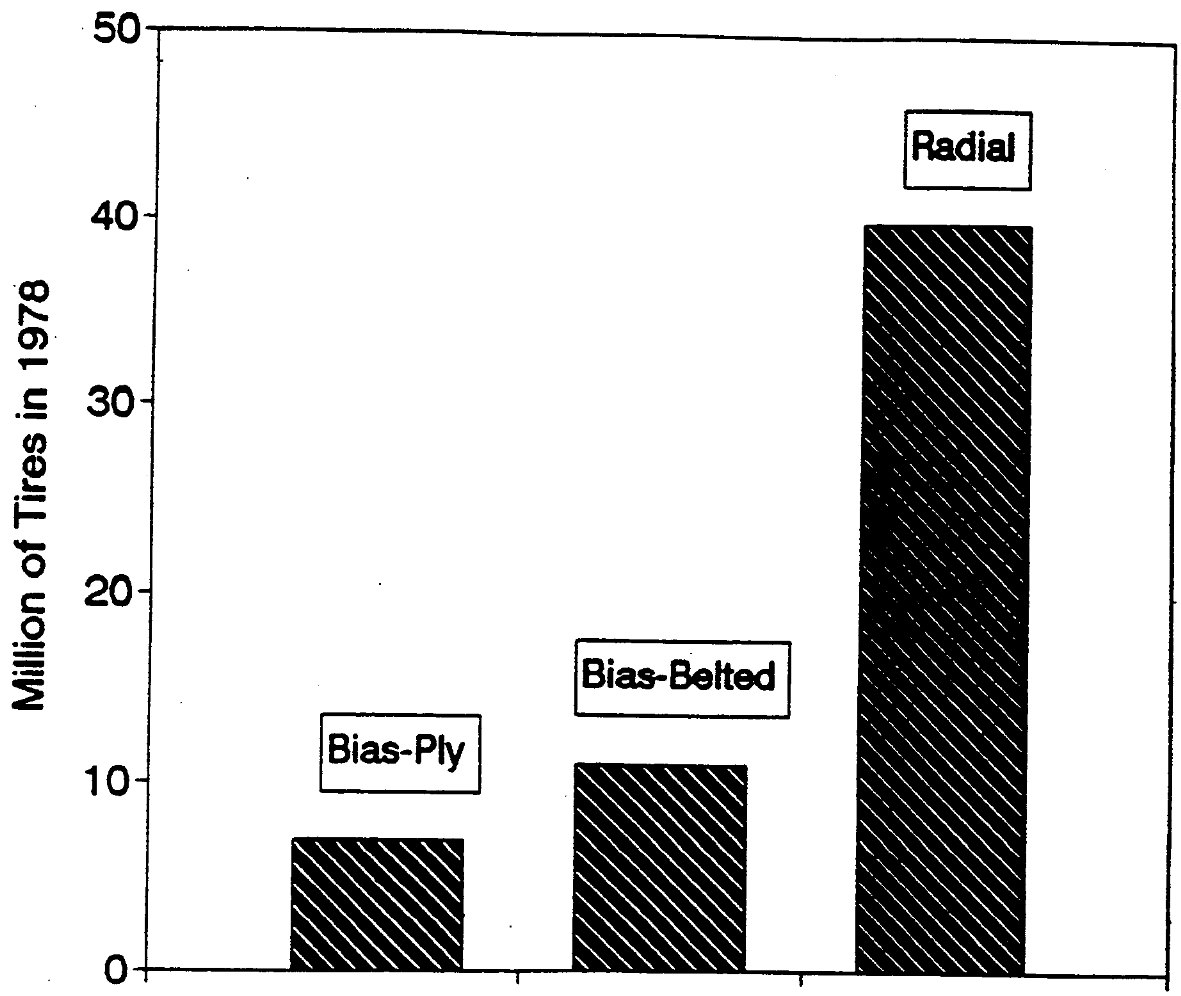


Fig. 2. Distribution of annual total tires by each tire type [3].

Table 3. Reinforcing materials in tire cord [3].

	Polyster (%)	Nylon (%)	Rayon (%)
Bias	95	4	1
Bias-Belt	100	0	0
Radial	95	0	5

Table 4. Reinforcing materials in tire belting [3].

	Steel (%)	Rayon (%)	Fiber-glass (%)
Bias-Belt	0	0	100
Radial	87	1	12

CHAPTER 3

MANUFACTURING SHREDDED TIRES

The shredded tires production is summarized in this chapter. The first section of this chapter describes the tire shredding process. The second part presents the types of shredders used to produce the material. The last part of this chapter describes three selected tire shredding facilities in Minnesota.

THE TIRE SHREDDING PROCESS

The tire shredding process is accomplished by a machine called the *shredder*. The machine produces particles of different size, which can be reduced further. There is no need for preliminary cutting of the tire beads. The machine is typically operated by two workers. One worker controls the operation switches of the shredder, while the other loads the tires by a front-loader or a back-hoe on the roller conveyor that feeds the tires to the shredder. The shredder consists of rotors and cutters in various arrangement. The shredded material is drawn to another conveyor located below the shredder. This conveyor transports the shredded material into a dump truck, or onto a stockpile.

The design of the shredder depends on the nature and volume of waste or disposal material to be reduced in size. Thus, the evolution of different types of shredders is the direct result of the need to shred various specialized sub-classes of material separately from, or in addition to, the general waste stream.

SHREDDERS

There are three designs of low-speed (sometimes called shear) shredders [4] which have evolved to meet varying application requirements in shredding different types of bulky, waste materials. These three shredders have different configurations of rotors and cutters. Low-speed shredders are used for the size reduction of waste materials such as municipal solid waste, discarded tires, and old appliances. There are two basic reasons for shredding any of these materials: densification to reduce volume, or preparation for down-stream processing operations.

Type I Shredder

The type I shear shredder evolved over the past 10 years for a specific application, namely, the preshearing of scrap nonferrous insulated wire and cable to prepare it for feeding into a mechanical reclamation system.

This type of shredder incorporates two counter-rotating shafts with knives that do not interract with each other. Instead, they cut against a stationary anvil bar equipped with replaceable and adjustable knives. At the same time, the knives have sufficient projection to pull apart the dense mass of wire and cable. As the knives on the two rotating shafts pass between the stationary knives they pull through, and cut into short lengths, the tangled mass of raw material. This shredder is not recommended for use in shredding tires because the stationary anvil is not able to cut steel-belted tires.

Figure 3 [4] illustrates a typical cross-section through cutting chamber of this shredder.

Type II Shredder

This shredder is the one which is used most. Typical applications include shredding:

1) municipal solid waste,
2) tires, where the only objective is size reduction for landfill,
3) oversized bulky waste, such as furniture, mattresses, and rolled carpets.

In almost all cases, this type of shredder uses two contra-rotating shafts with knives which intermesh with each other. The material is drawn into the pinch point and sheared or torn apart rather than cut. The two shafts run at different speeds and torque outputs. Figure 4 [4] shows a cross-section of this type of shredder.

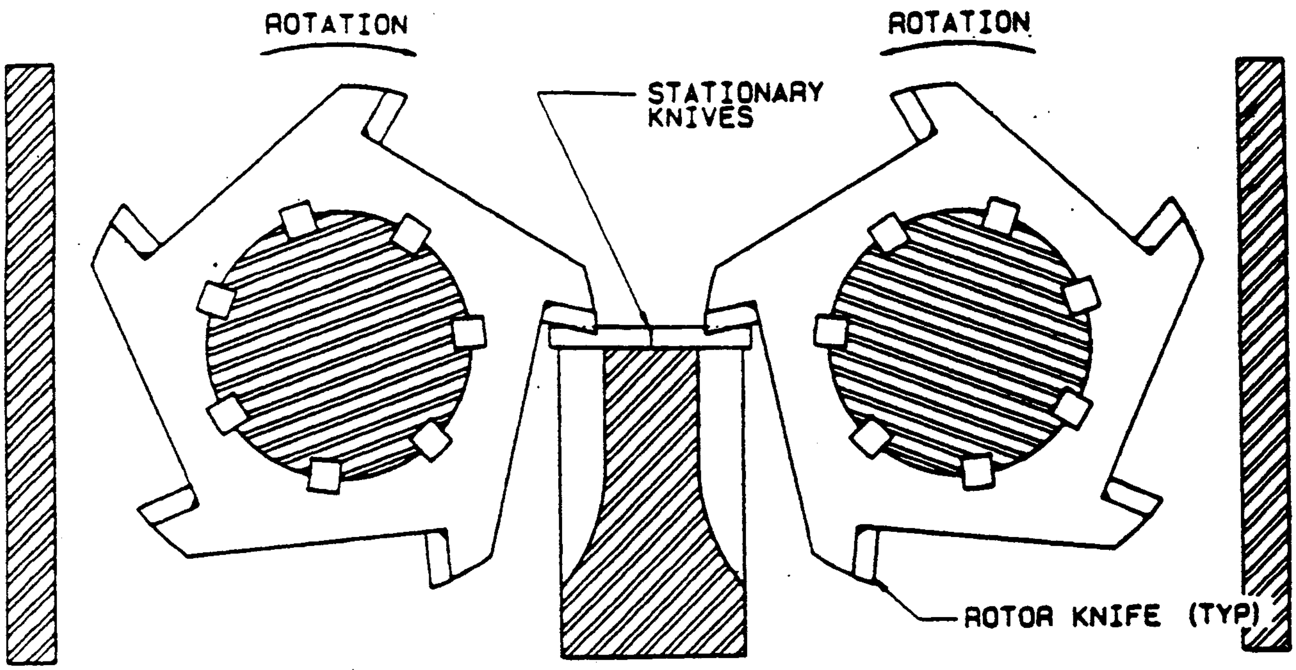


Fig. 3. Typical cross-section of type I shredder [4].

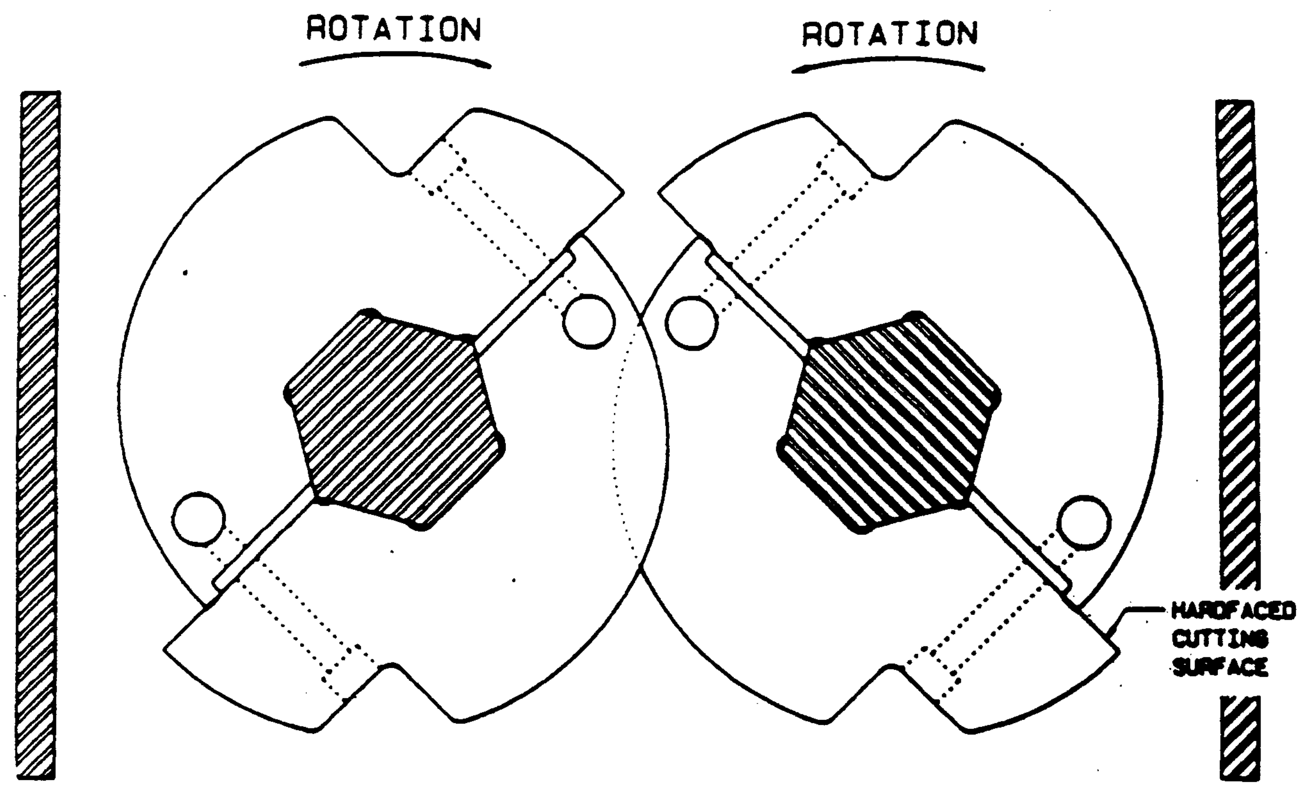


Fig. 4. Typical cross-section of type II shredder [4].

Type III Shredder

This type of shredder is less commonly used than the type II shredder. Like the type I shredder, this third type is designed with a specific waste stream in mind, and with a specific end use objective for the product generated; particularly if the shredder output material must be reasonably uniform in shape and size.

The type III shredder design incorporates features from the first two types. It combines the cutting of edges as in the type I shredder and the tearing action of the edge/rotor as in the type II shredder. This shredder has no anvil but the shredding process is enhanced by means of star shaped feed rolls which push the material into the cutting zone. Figure 5 illustrates a typical cross-section through the cutting chamber. This type of shredder has found some application in shredding tires.

SELECTED MINNESOTA TIRE SHREDDING PROCESS FACILITIES

Three shredding facilities around the Twin Cities area are described in this section.

Maust Tire Recyclers, Inc

The plant is located at the junction of Trunk Highway 13 and Trunk Highway 101, south of the city of Savage in Dakota County, Minnesota.

The primary objective of this plant is to reduce tires to a size that can be used as fuel. However, this plant produces different sizes that are applicable to roadway construction. The shredding plant consists of three Saturn shredders Model 52-32 classified as Type II shredders. The shredders have a throughput for truck tires of 90-100 tires/hr, and for passenger tires of 600-700 tires/hr. The shredders have two shafts each 7 in. in diameter. Each shaft has 12 cutters, each with an 18-in. outer diameter, and has three rotor knives that are 3 in. long. The shredding of used tires is accomplished by the following procedure. First, the used tires are transported from the location of the

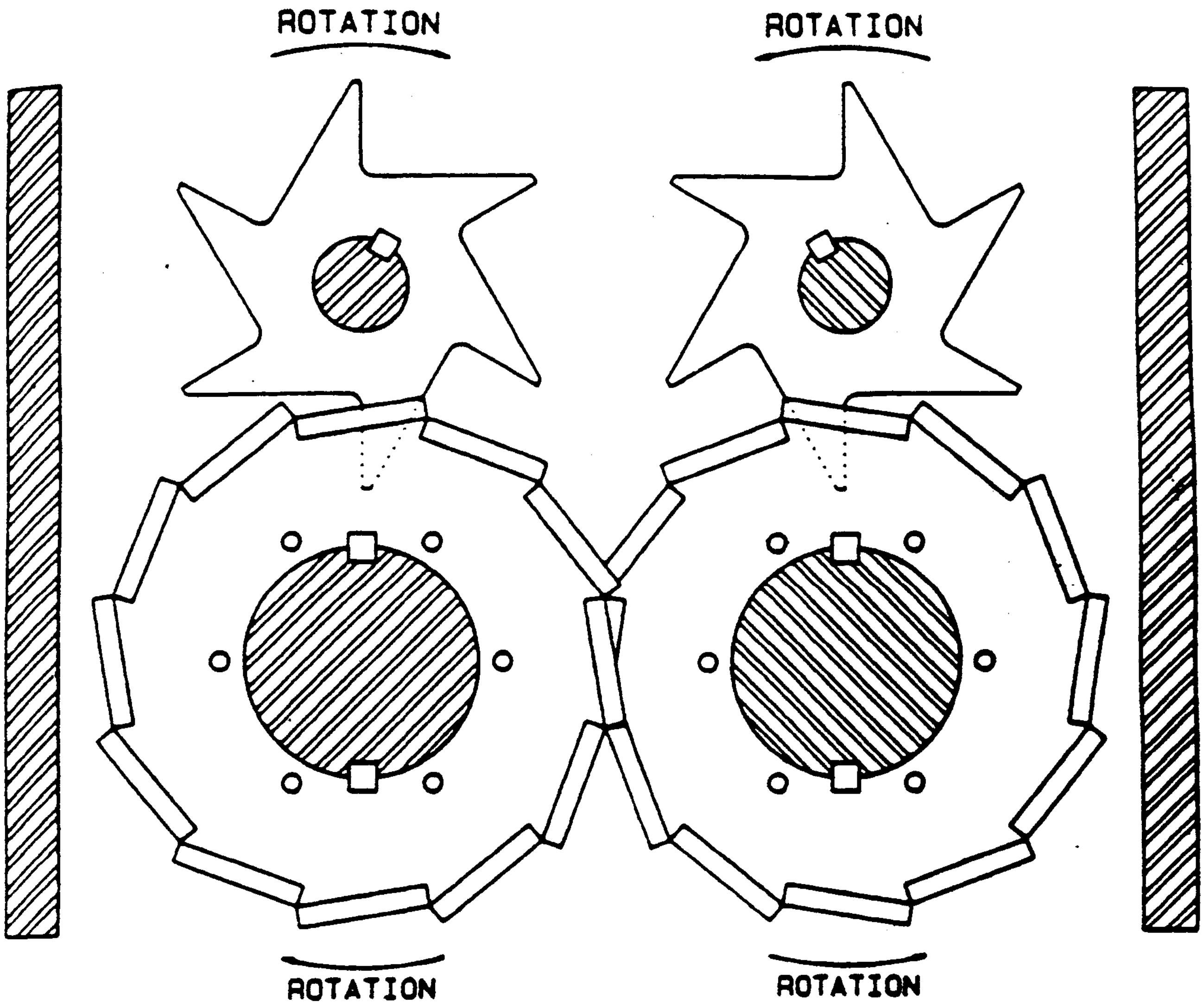


Fig. 5. Typical cross-section of type III shredder [4].

stockpiles to the shredding plant. Second, tires are loaded into the primary shredder. The output material is transported on a conveyor that feeds the material to the secondary shredder that further reduces its size. The output material from this shredder is carried on another conveyor that feeds the material to the tertiary shredder. The output material is exposed to a magnetic field located at the beginning of a shallow cylinder to remove the steel wires embedded in the shredded tire pieces. There are three sizes of sieves placed next to each other located at the bottom of the shallow cylinder. The sieve sizes are 1, 2, and 3 in. In case the shredded material does not meet requiredclassification, the material is brought back to the tertiary shredder by a conveyor to be reduced until it meets the specification. There are three sorted stockpiles of used tires in Maust Tire Recyclers. These stockpiles consist of passenger tires, light-truck tires, and heavy-truck tires.

First State Tire, Inc.

First State Tire, Inc. does not operate from one location. Instead, mobile shredding equipment is transported to the customer's location where tires need to be shredded. The equipment consists of a Saturn shredder Model 52-26 type II mounted on a trailer, two rolling conveyors, front-loader, and truck. The shredder has a throughput rate for truck tires of 75-100 tires/hr, and for passenger tires of 500-700 tires/hr. The shredded tires are supplied to township and county roads where they are used as subgrade support.

The operation of shredding tires is done as follows. First, the tires are loaded by a front-loader on the first rolling conveyor which feeds the tires to the shredder that has two shafts approximately 6 in. in diameter. Each shaft has 15 cutters, 14 in. in outer diameter. Each cutter has three rotor knives, 3 in. long. Next, the shredded tires are transported on a conveyor into the truck.

Bellaire Sanitation, Inc.

This enterprise is located at the junction of Highway 12 and 75, in Stillwater, Minnesota. The site has an area of about 40 Acres. There are two stockpiles of tires, and Saturn shredder Model 52-26 classified as Type II mounted on the bed of a truck. The shredder has a throughput rate for truck tires of 75-100 tires/hr, and for passenger tires of 500-700 tires/hr. The shredder has the same description as that of First State Tire. However, on each shaft, there are 35 cutters with 1.5 in. long rotor knives. The stockpiles are mostly formed of passenger tires. The shredded tires are used for landfill and as support for weak subgrades.

The procedure of shredding tires is similar to that of the First State Tire, Inc.

CHAPTER 4

USE OF SHREDDED TIRES IN GEOTECHNICAL/PAVEMENT PROJECTS

The use of shredded tires in geotechnical/pavement projects is presented in this chapter. It contains two sections. The first section summarizes the literature and describes the use of the discarded tires in their original or shredded form in typical projects. The second section covers and describes selected Minnesota projects where tires have been used as subgrade support.

LITERATURE REVIEW AND GENERAL PROJECT DESCRIPTIONS

For centuries, geotechnical and highway construction projects have been built using geo-materials in their original or improved composition. With natural resources decreasing, and the demand for more efficient and less costly design, it has become apparent that improving the mechanical properties of geo-materials opens new avenues. This resulted in a concept called "reinforced earth".

In the late 1950's, Vidal [5] developed the idea for reinforced earth while visiting a sandy beach on the Mediterranean Sea. He toyed with the sand, arranging it in piles, which quickly slid down forming cones with an angle of repose that always remained about the same. He then placed rows of pine needles between layers of sand and discovered that the angle of repose tended more toward the vertical. Essentially, he reinforced the sand so that the internal friction between the sand and the pine needles held the sand in place. This concept was verified in 1965 when he designed the first reinforced earth embankment in France [6].

The first reinforced earth installation in the United States was placed by the California Division of Highways in 1972 on Route 39 in Los Angeles. Prior to that time the only installations were in France, Canada, and Africa [7]. The projects used mainly strips of steel of various length and geometrical arrangement. Recently, materials such as geosynthetics have become more popular than steel. For a satisfactory reinforced earth construction, Vidal suggests that the soil has to be composed of granular materials having an angle of internal friction of at least 25° to develop adequate frictional resistance between the soil and the reinforcing material. He also suggests that no more than 15% should be finer than No.200 material [5]. A preliminary laboratory investigation reported by Singh and Lee [8] confirmed somewhat the guide criteria suggested by Vidal [5].

One advantage of "reinforced earth" is that it permits the construction of an embankment with nearly vertical side slopes without external restraint as provided by a retaining wall. Thus, the facing serves only to prevent local sloughing and erosion. Within practical limits there is no height limitation except for the bearing capacity of the foundation materials. Also, its flexiblility permits construction over foundations which would not normally be suitable for conventional retaining walls. This technique appears to have excellent potential for replacing relatively high retaining structures where soil conditions are suitable. The disadvantage of this system is that it does not reduce the weight of the geotechnical structure which, in many cases, may lead to failure of the surrounding soil mass. To remedy this problem, man-made or natural lightweight materials such as wood chips and tires in their original or shredded form, can be used as a substitute for the soil.

Whole Tire Applications

California

One of the first projects to explore the use of discarded tires in highway construction was initiated by California Department of Transportation (CalTrans) [1]. One application was sought for use of discarded truck tires in an embankment to control shoulder erosion. Route 32, in Tehama County, is a narrow winding mountain roadway whose shoulders were being eroded by both rainfall and snowmelt. In this project, whole truck tires were used to reinforce the road shoulder. The tires were connected using clips which were made from 1/2 in.

steel reinforcing bar to hold the tires in point contact thereby forming a continuous mat. Salvage anchor posts were used to secure the tire assembly to the embankment. The tire mats were covered by approximately 28-in. of compacted permeable material.

Another project was the installation of discarded truck tires in a low velocity drainage channel with highly erodible soil to control slope erosion. On Route 5, in Fresno County, the channel banks had severly eroded up to the adjacent private property. The truck tires were stacked side by side, seven to eight tires high against the banks. To secure the tires in place, posts were driven at each end of the unit with No. 8 gauge wire strung horizontally between them. Wire was then laced through each stack of tires and secured to the horizontal wires. The tire mats were covered with 18-in. layer of compacted sandy loam.

The third project was the construction of discarded automobile tire barriers which provided temporary windbreaks for protecting trees. On State Route 111 south of I-10 in Riverside County near Palm Springs, the blowsand is abrasive. It damages vehicles, reduces visibility and is hazardous to motorists. In this project, two basic methods of impounding wind transported sand with discarded tires were accomplished. One was the laying out of a mat tires, and the other was the creation of barrier walls perpendicular to the direction of the sand movement. The mat method was extremely tire-intensive. Approximately twice as many tires were employed as with the barrier method, with essentially the same effectiveness.

The results of this research indicated that the construction of shoulder reinforcement and channel slope protection with discarded tires provide an immediate solution for minor contracts and projects. However, it was not cost-effective as the result of being extremely labor-intensive.

Minnesota

The Minnesota Department of Natural Resources, Division of Forestry (DNR-Forestry), in Saint Louis County, Minnesota, set out to design a series of roadway test sections to determine the feasibility of applying discarded tires and the best configuration to provide necesssary support for the subgrade [9]. The Hedbom Forest Road near Floodwood, in Minnesota was used for the testing. The road had been used to access a large block of state forest land. The project consisted of eight test sections, each 400 ft long, with a standard geotextile section on each end of the test area as a control section. The project consisted of upgrading an existing low standard road across six miles of peat, constructed originally with corduroy to reinforce the weak subgrade. The depth of peat ranged from 5 to 17 ft. The tire mats to be tested were placed fullwidth on the top of a geotextile fabric that was placed at the base of the embankment widening areas. To construct the mats, the tires were tied together with a nylon toggle strap. The strap was inserted into prepunched holes in the tires. The tire mats were covered with a 12-in. deep silty sand common borrow soil. Based on settlement plates placed on the top of the fabric to measure the tire mat subgrade settlements at the passing of a 6-ton per axle truck over the silty sand, it was deduced that no one section has settled more than any other. The settlements were less than would be expected with conventional soil embankments. The methods used to tie the mats together for these studies was highly labor-intensive.

Laboratory Tests on Shredded Tires

Strength

A laboratory investigation was conducted by CalTrans on the stabilizing effects of including shredded tires in typical highway embankment soils [10]. The objective of the study was to determine the strength parameters of the reinforced soil. The results from triaxial test conducted on 13 in. x 27 in. specimen showed that including layers of shredded tires finer than 3 in. in slightly plastic, silty clay soil increased the shear strength and strains at failure. The angle of internal friction was about 23° and the cohesion was about 3 psi for the reinforced silty clay soil, in contrast to the angle of friction of about 24°and no cohesion for the silty clay soil.

Permeability

CalTrans also conducted laboratory investigation to determine the permeability coefficient of shredded tires [11]. The constant head permeability tests were run on two types of shredded tires: The first type consisted of pieces greater than 2 in. and less than 3 in., fairly regular in size and shape. The other type contained smaller pieces. These types were referred to as "2 in. square" and "2 in. shredded" , respectively. Figures 6 and 7 show the grading analysis of the two types of shredded tires, respectively. To evaluate the permeability of the two types of shredded tires, a constant head permeameter was constructed. Permeability tests were conducted on 11.8 in. by 48 in. specimen for 24 hours on both compacted and loosely placed samples of the two types of shredded tires. Permeability values determined for the 2 in. square and 2 in. shredded were within the same order of magnitude, 10,000 ft/day, and were comparable to the permeability values of 1 1/2 in. by 3/4 in. CalTrans Class 3 aggregate.

Compressibility

In addition to constant head permeability tests, the two types of shredded tires were subjected at CalTrans to a one-dimensional compressibility test. Three test types were conducted: 1) a loosely placed 9 in. high column of material was subjected to a 2 psi surcharge, 2) the surcharged column of material was vibrated for 8 minutes, and 3) after vibrating the surcharge was removed. The vertical displacement recorded during compressibility testing showed that the used tire materials can be subjected to large deformation. When subjected to static load, the vertical strain was about 25% for the 2 in. shredded and 12% for the 2 in. square. However, when the two materials were vibrated for 8 minutes, the strain increased by 3% for the 2 in. shredded and 2% for the 2 in. square. The swelling was measured when the static load was removed. The recoverable strain was 12% for the 2 in. shredded and 8% for the 2 in. square.

SELECTED MINNESOTA PROJECTS

To avoid the labor-intensity associated with the tire mat construction, the concept of using shredded tires as lightweight fill was developed. There are a number of projects in Minnesota in which shredded tires were used as lightweight fill subgrade. Nine of these are discusse here.

Benton County Project

This project was constructed by the Highway Department in Foley in 1989 in compliance with a Minnesota DNR permit. The roadway is located on Trunk Highway 21 north of city of Rice, Minnesota, which is on U.S.10 in the northwest corner of Benton County [12]. The highway is a main arterial road leading into the city of Rice and has an average daily traffic volume of 380 vehicles with a large proportion of heavy trucks. The portion suffering distress was approximately 250 ft long. There was standing water in this area and during the wet years, the water rose to the elevation of the roadway. The original construction was stable but subsequent additions of earthen fill material to raise the roadway above high water mark overloaded the underlying peat causing the embankment to fail. Therefore, replacement of a portion of the heavier earthern fill material with a lightweight shredded tire product was considered.

The site was characterized by approximately 12 ft of peat or muck type material.

The shredded tire material was provided by First State Tire, Inc., and the average size of shredded tires was about 12 in. in length.The grade was excavated to a point approximately 3 ft above the level of the low ground. Geofabric was laid in the bottom of the excavation and then a layer of 3 ft of shredded tires was placed and compacted with a Caterpillar loader. After compaction of the shredded tires, an additional layer of geofabric was installed on the top of the shredded tires.The fabric was then covered with 12 in. of granular material that was compacted to 100% of standard Proctor density (ASTM D698). Before paving operations began, the embankment was again checked for signs of distress or movement.

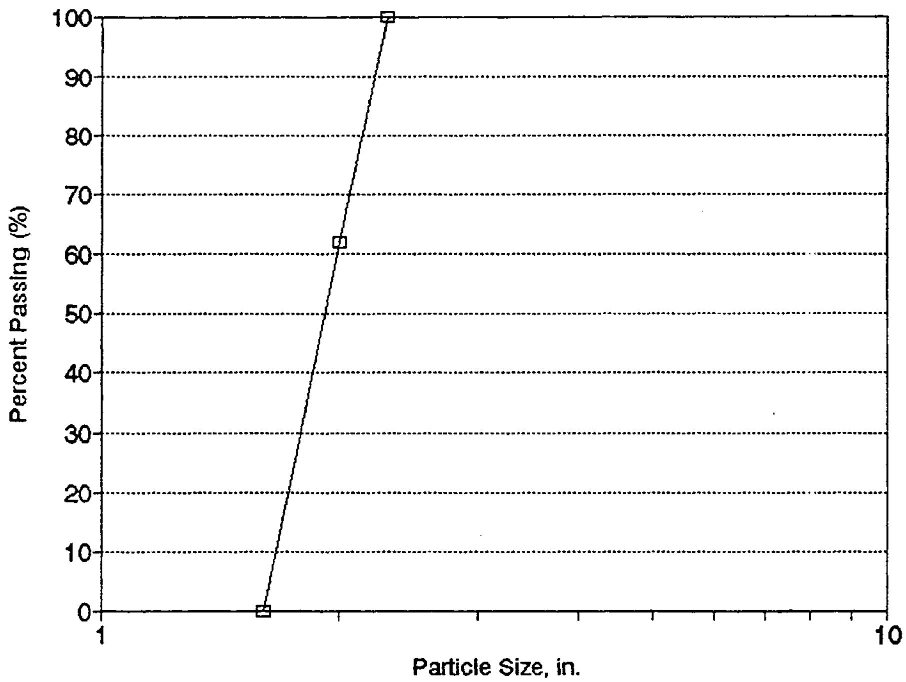


Fig. 6. Particle size distribution of 2 in. square tires [11].

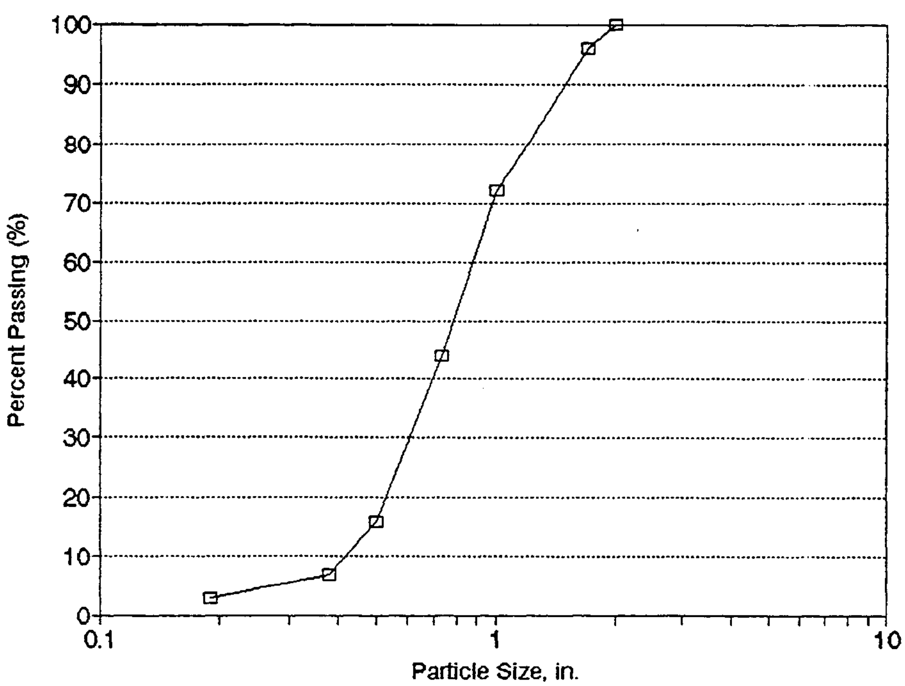


Fig. 7. Particle size distribution of 2 in. shredded tires [11].

Scott County Project

This project, constructed by Ames Construction, Inc., used shredded tires as lightweight backfill over an existing watermain. It was located between County Road 82 to Quincy Street, in Scott County, in the City of Prior Lake, Minnesota. This project started July 1991. The water elevation was at 900.5 ft, and swamp deposits characterized the site.

The source of the shredded tires used in this project was Maust Tire Recycles, Inc., in Savage. The size of shredded tires was 100% finer than 3 in.

A layer of 3 ft of shredded tires was placed and compacted with a Caterpillar dozer on the top of a 3-ft thick layer of woodchips. Next, geotextile fabric was placed over the shredded tires, and another 3-ft layer of shredded tires was placed on the top of the first layer. Then it was compacted with a dozer and wrapped with a geotextile fabric. The fabric was covered with approximately 24 in. of fill material. The designed cross-section is shown in Fig.8.

Athens Township Road Project

This road was built by First State Tire, Inc., in July 1991, and contained shredded tires as lightweight fill over the Athens Township Road No.T194 constructed on a series of peat swamps. The road project is located north of County Road 12, in Isanti County, Minnesota.

Athens T194 is a sand-filled road that has been repaired frequently for the last 10 years. Every year the Athens Township had to add more sand to the road to raise the grade. Because of the excessive weight on the peat subgrade, the road settled continuously. Therefore, it was decided to use shredded tires as lightweight fill on the sand to minimize the settlement of the peat.

Approximately 2 ft of granular material from the driving surface was excavated. Next, a geotextile fabric was placed on the top of the sand, then a 3-ft layer of shredded tires was placed on the top of the fabric with a Caterpillar front-loader. After that the shredded tires were compacted with the same front-loader. Another layer of fabric was placed on the top of the shredded tires, and covered with an 18-in. layer of sand.

Prior Lake City Project

The City of Prior Lake designed a new roadway at the intersection of Duluth and Tower Avenues in Prior Lake, Minnesota. In order to maintain embankment stability and minimize settlements of the underlying peat, it was decided to use lightweight fill for a portion of the embankment.

The site was characterized by 30-ft deep swamp deposits. Figure 9 shows a soil profile along Duluth Avenue with indication of the designed embankment.

The source of the shredded tires was the Maust Tire Recyclers in Savage, Minnesota. The specification for the particle size of shredded tires used on the project is shown in Appendix A. This specification was taken from the guide specification for lightweight fill material used in the research work done by the DNR [9]; the DNR has developed a guide specification for the particle sizedistribution of shredded tires as lightweight fill material. This specification restricts shredded tire pieces to not more than 12 in. in length. It was decided to use shredded tires that are 100% finer than 4 in.

A geotextile fabric comparable to Marifi 500X was placed on a layer of woodchips. Next, 3 ft of shredded tires were placed with loaders on the top of the fabric, and compacted with dozers. The compaction was controlled by visual observation. The number of doser passes was considered effective when naked eye observation indicated that the shredded tire layer was no longer settling. Another layer of fabric was placed on the top of shredded tires layer. Upon completion of the fabric layer, a 6-in. sand subbase, and 24 in. of Class 5 aggregate base layers were placed on the top of the fabric. Figure 10 depicts the designed cross-section of the road. This design was based on the assumption of an R-value equal to 10 for the shredded tires. The primary road design assumed an R-value equal to 5. However, when the shredded tires were subjected to the Class 5 aggregate base only, a settlement of 6 in. had occured in the shredded tire layer. To make up for that settlement a 6 in. sand subbase was

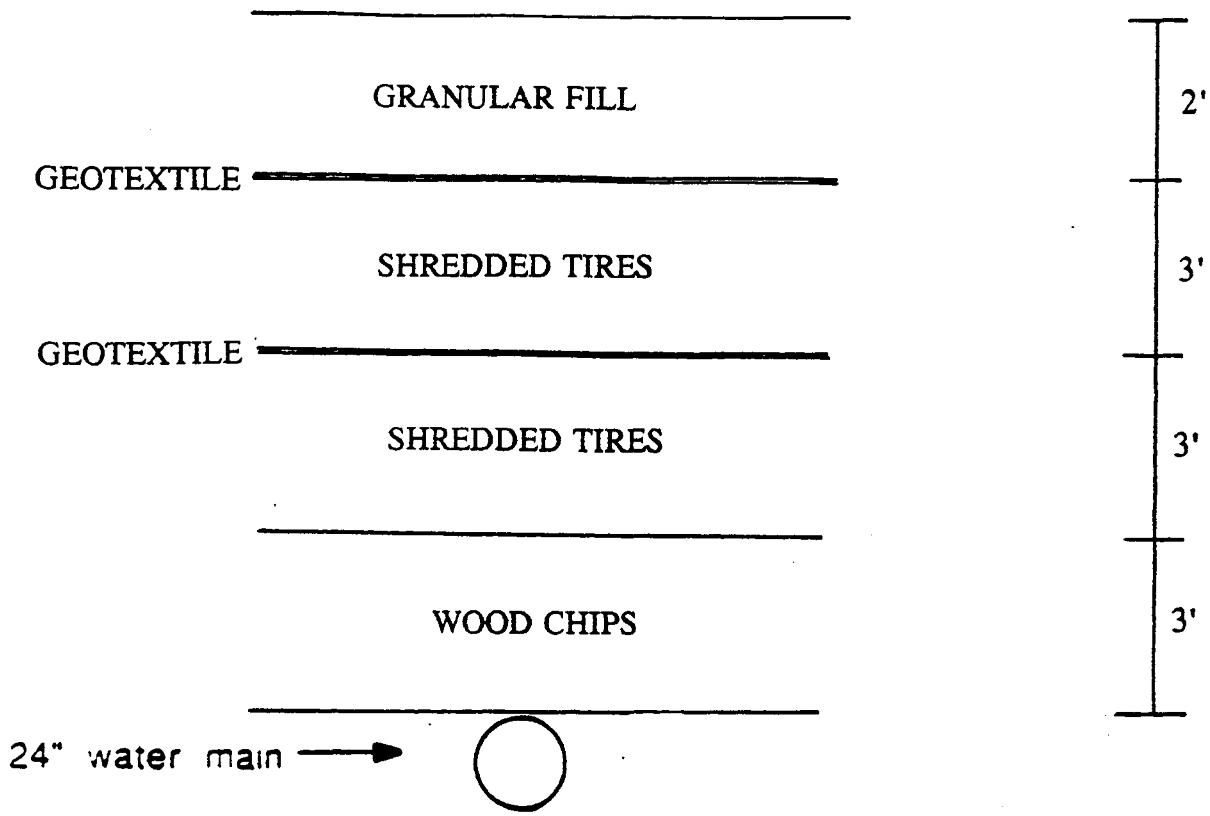


Fig. 8. Cross-section of Scott County project.

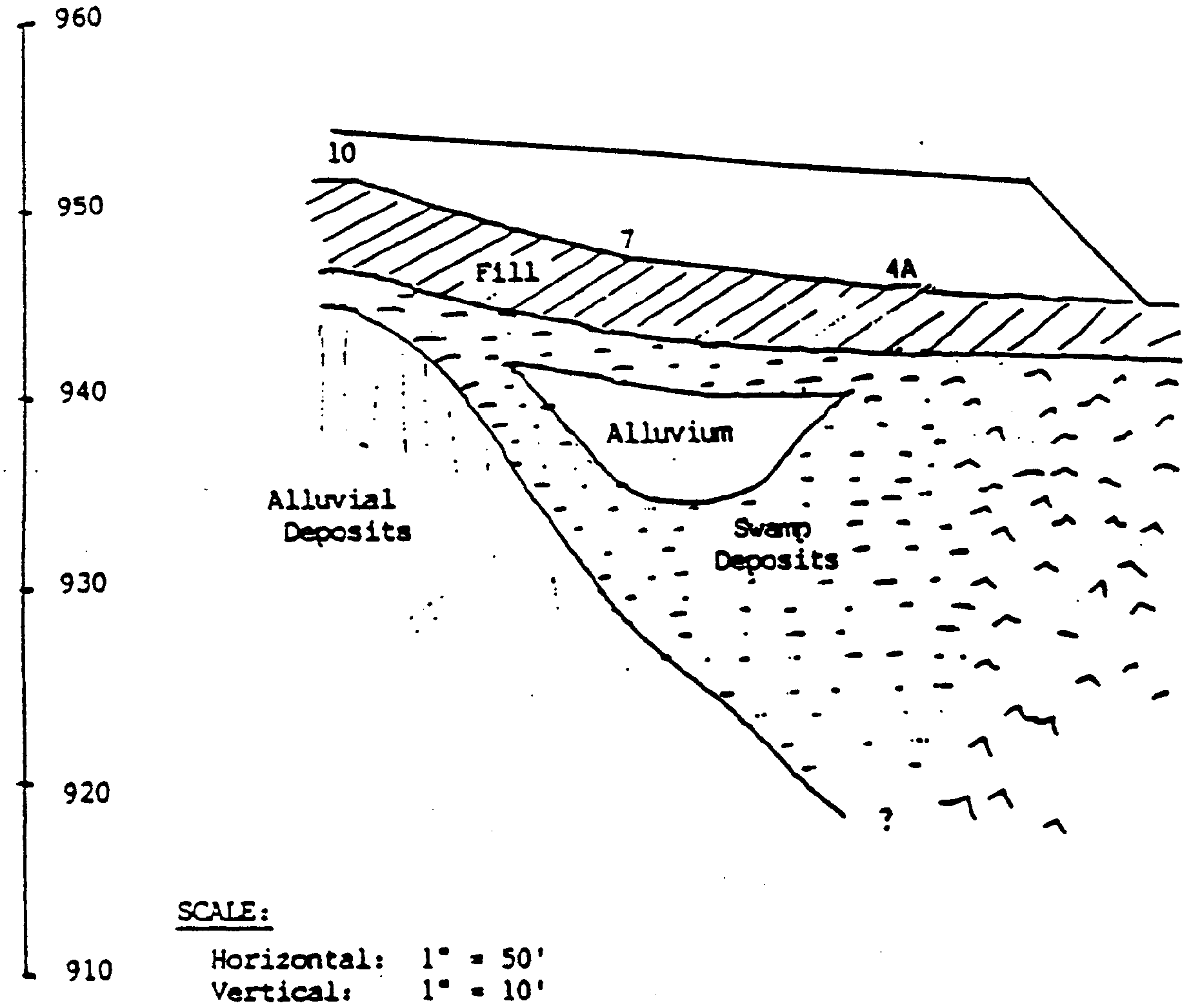


Fig. 9. Soil profile along Duluth Avenue.

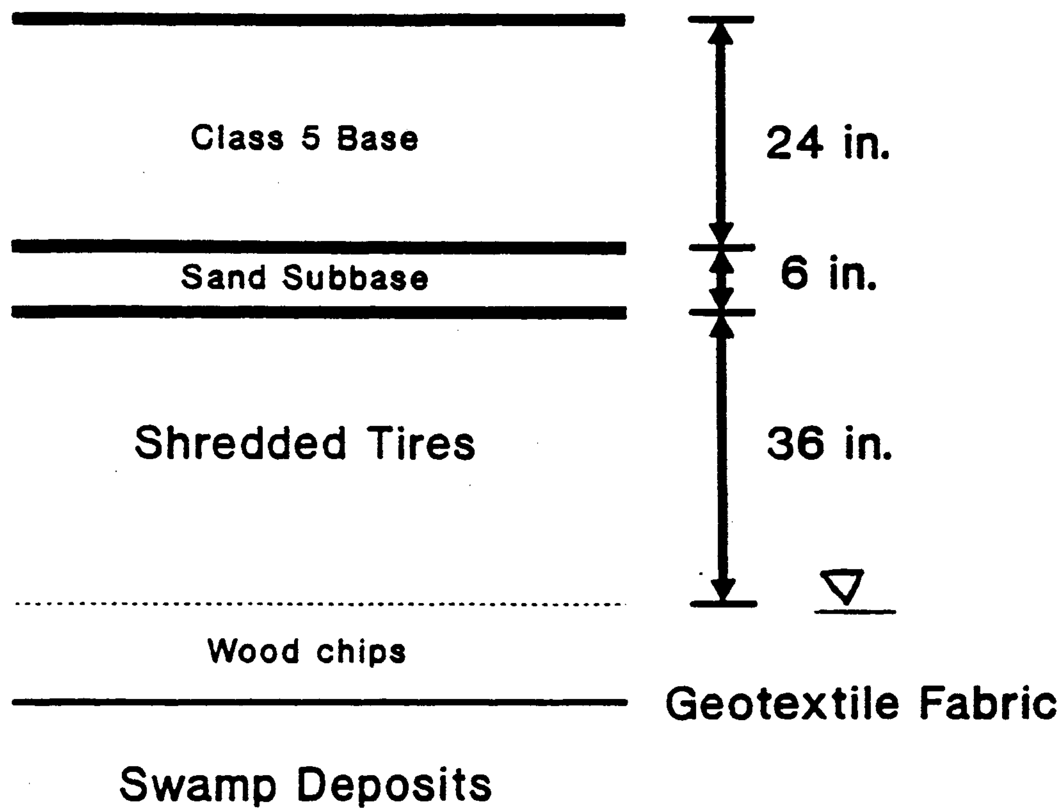


Fig. 10. Cross-section of Duluth Avenue.

placed between the shredded tires and the base. The backcalculation of the R-value for the final road design was about 10.

Field tests were conducted with the objective to determine the settlements and the modulus of subgrade reaction (k) of the shredded tire layer, and the elastic modulus (E) of the Class 5 aggregate base. Two settlement plates were installed on the top of the second layer of fabric to measure the settlement of shredded tires layer. To estimate the modulus of subgrade reaction (k) of the shredded tire subgrade, a plate load test directly on shredded tires was performed by Twin City Testing. The plate was 12 in. in diameter. For the estimation of the elastic modulus (E) of Class 5 aggregate base at different locations, a falling weight deflectometer (FWD) test was performed on the top of the Class 5 aggregate base by Mn/DOT. The diameter of the plate used was 18 in. The measurements were recorded at 7 sensors located at the center of plate, and 11.81 in., 19.68 in., 31.50 in., 47.24 in., 62.99 in., and 78.74 in. from the center of the plate, respectively.

During the placement of the Class 5 aggregate base and subbase, the shredded tires settled by approximately 6 in. The relationship between the settlement of the two plates and time is shown in Fig.11. The results from the plate load testing are shown in Fig.12. This figure shows that the layer of shredded tires exhibited a large displacement due to the vertical stress ranging from 1 to 7 psi. The modulus of subgrade reaction (k) of shredded tires was about 2.8 pci.

The deflections taken from the FWD-test were plotted a a function of different locations along the length of the road for normalized vertical load of 3,000 lbs. The latter is shown in Fig.13; the maximum deflection is about 0.06 in.

The estimated cost of producing less than 4 in. in size shredded tires by the Maust Tire Recyclers, Inc for this project was $0.05/ft^3$. The total volume of shredded tires used for this project was 159,040 ft^3. Therefore, the total cost of shredded tires was $7,952.

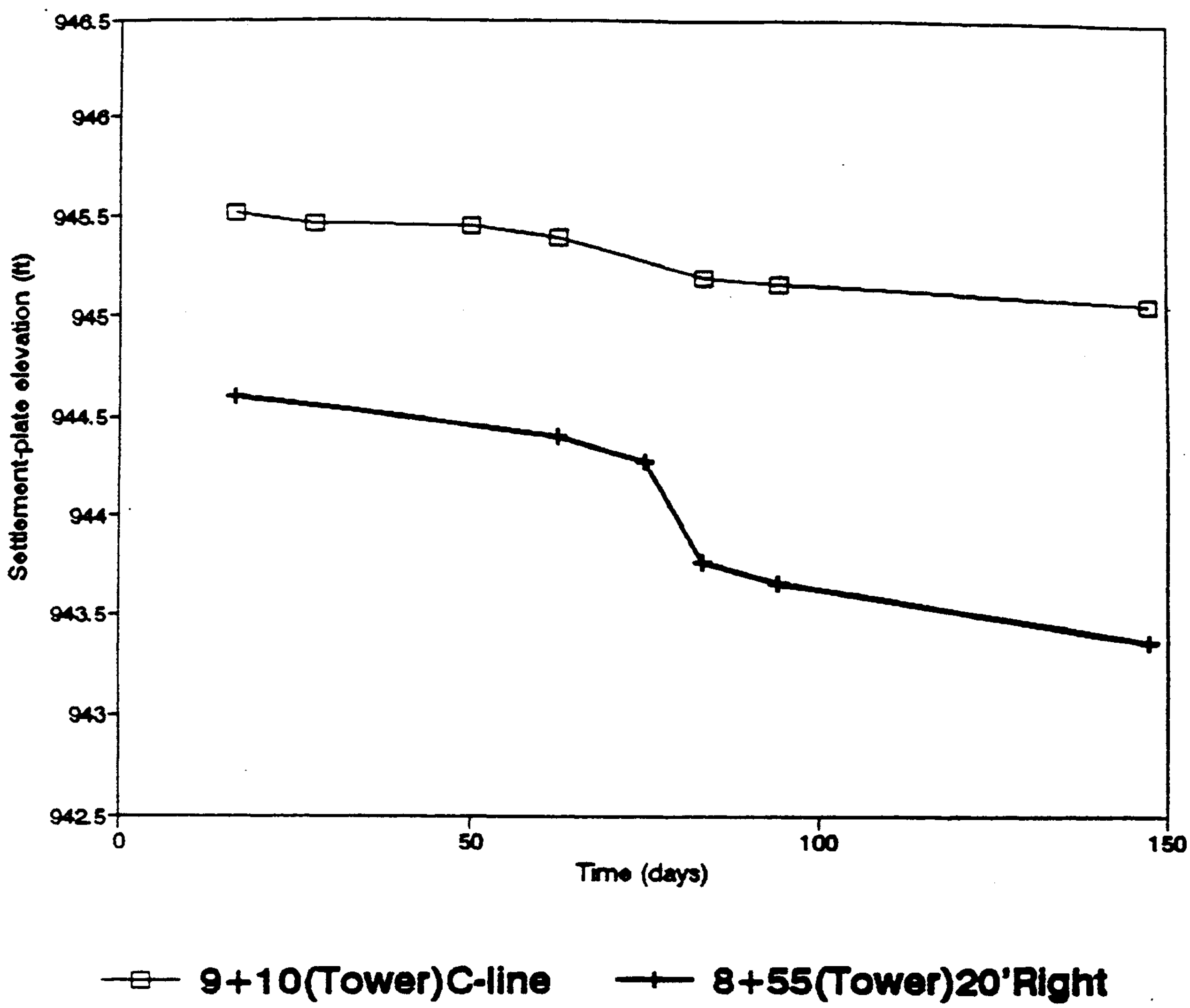


Fig. 11. Settlement measurements for Prior Lake project.

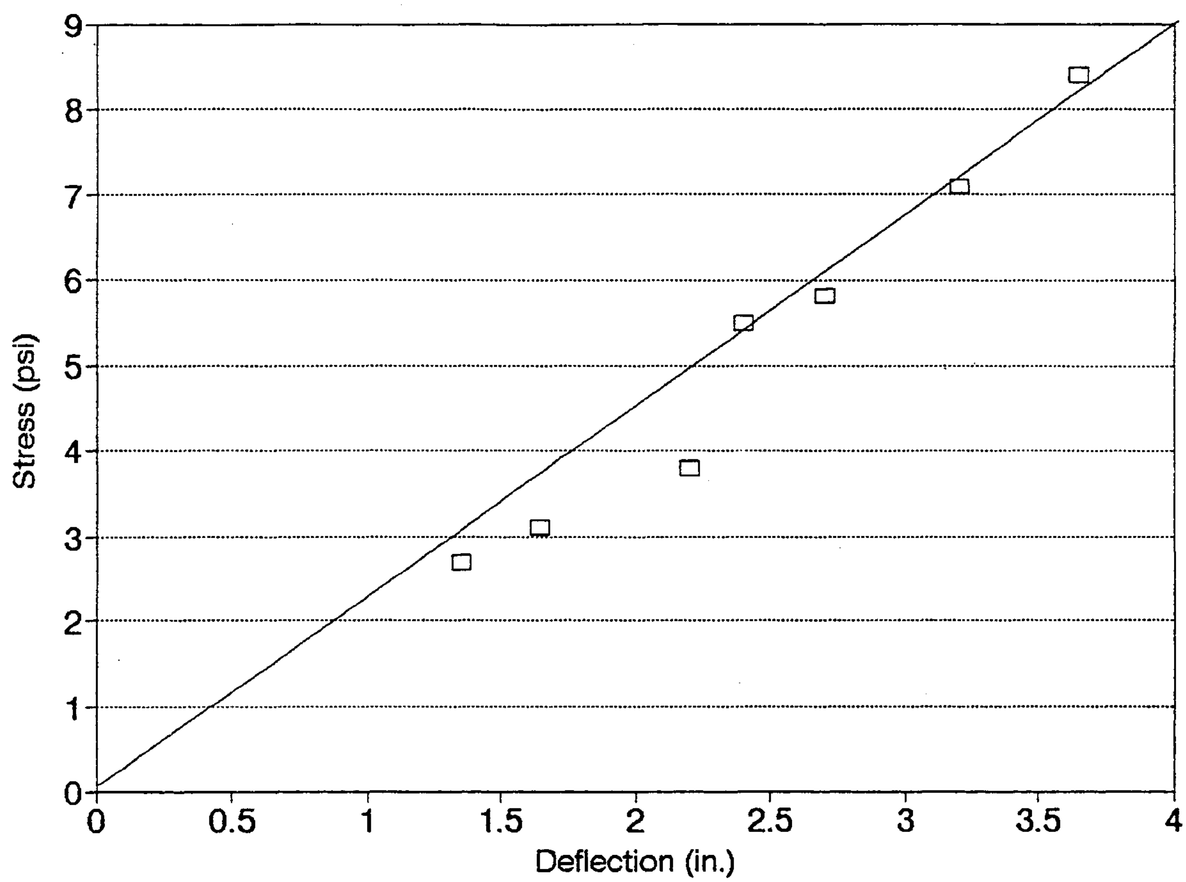


Fig. 12. Vertical stress versus deflection for Prior Lake project.

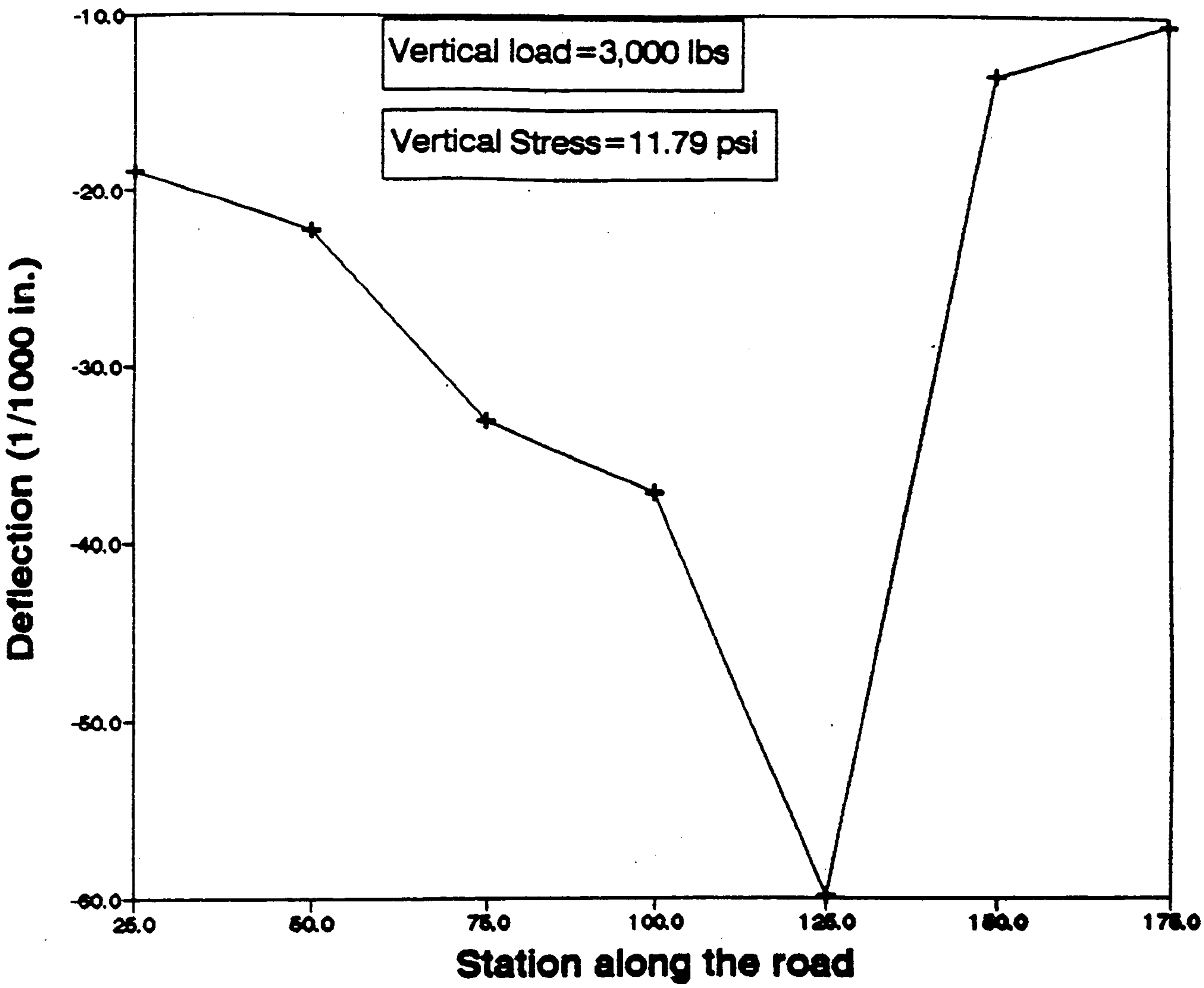


Fig. 13. FWD deflection measurements for 3,000-lb load.

Based on this project, the following conclusions can be made:

1) Shredded tire chips of the size utilized (smaller than 4 in.) are very easy to place and grade.
2) After placement and compaction of the tire chips, the subgrade modulus of the material is low of about 2.8 pci. Therefore, sufficient soil subbase and base must be placed above the tires for pavement support.
3) Based on this project, it might be suggested that pavement design using shredded tire subgrades should assume an R-value of 5 for the tire material.
4) The FWD data showed that at a 3,000-lb load, the maximum deflection was about 0.06 in.

Eden Prairie Project

This project was located between Old Shady Oak Road and New County Road No. 61, in Eden Prairie, Minnesota [9]. In order to reduce the settlement of the earth embankment resting on peat, it was decided to replace the existing soil with shredded tires.

The site was characterized by approximately 40 ft depth of soft organic soil. During the construction of the road with soil fill, the earth embankment failed. The road was inadvertently overfilled, resulting in nearly 30 ft of soil fill placed over the soft organic soil. The embankment punched into the soft soil and settled to an elevation that was below the designed road subgrade. Therefore, shredded tires were used as lightweight fill to reduce the settlement of the embankment.

The source of shredded tires was First State Tire, Inc. The size of the shredded tire material used was about 6 to 8 in. in width by 12 to 24 in. in length.

Ten to 14 ft depth of the existing mineral soil was excavated. A geotextile fabric was placed on the top of a 6-ft layer of sand. Next, loose lifts of shredded tires ranging from 2 to 3 ft in thickness were placed on the top of the fabric by loaders, and these lifts were compacted by several passes of the tracks of a Caterpillar D-8 dozer. After reaching a 9-ft layer of compacted shredded tires, this layer was capped by another layer of geotextile fabric. Upon completion of the geotextile fabric placement, a 4-ft layer of compacted common borrow soil was placed over the fabric. The pavement section was then constructed, consisting of 12 in. of crushed limestone base aggregate and 3.5 in. bituminous base course. The roadway cross-section is shown in Fig.14.

The objective of the field tests was to monitor settlements of the soft organic soils and the shredded tires layer during and after construction. Four settlement plates were placed equidistant from each other on the top of the first layer of fabric, to monitor the settlements of the sand during placement and compaction of the shredded tire layer. Two other settlement plates were installed to measure the settlements of the shredded tire layer subjected to 4 ft of compacted common borrow soil. The elevations of the settlement plates were recorded with surveying equipment [9].

Settlement monitoring plates indicated the base of the sand had stopped settling during the embankment reconstruction with the shredded tires. Figures 15 and 16 show the displacement of the 4 settlement plates located on the top of the first layer of fabric as a function of time. The monitoring devices placed on the top of shredded tires indicated some consolidation of the shredded tires after the common borrow soil was in place. After compaction of the common borrow soil, there was an additional consolidation of the shredded tires which ranged from 8 to 10% of its total thickness [9].

The project used a volume of shredded tires of about 110,700 ft^3. The estimated cost of producing 6 to 8 in. in width and 12 to 24 in. in length shredded tire pieces was \$0.24/ft^3. Therefore, the total cost of shredded tires was \$27,060.

From the limited experience on this project, these following conclusions can be reached:

1) Shredded tire pieces of about 1 ft^2 in surface area are easily compacted with a Caterpillar D-8 dozer.

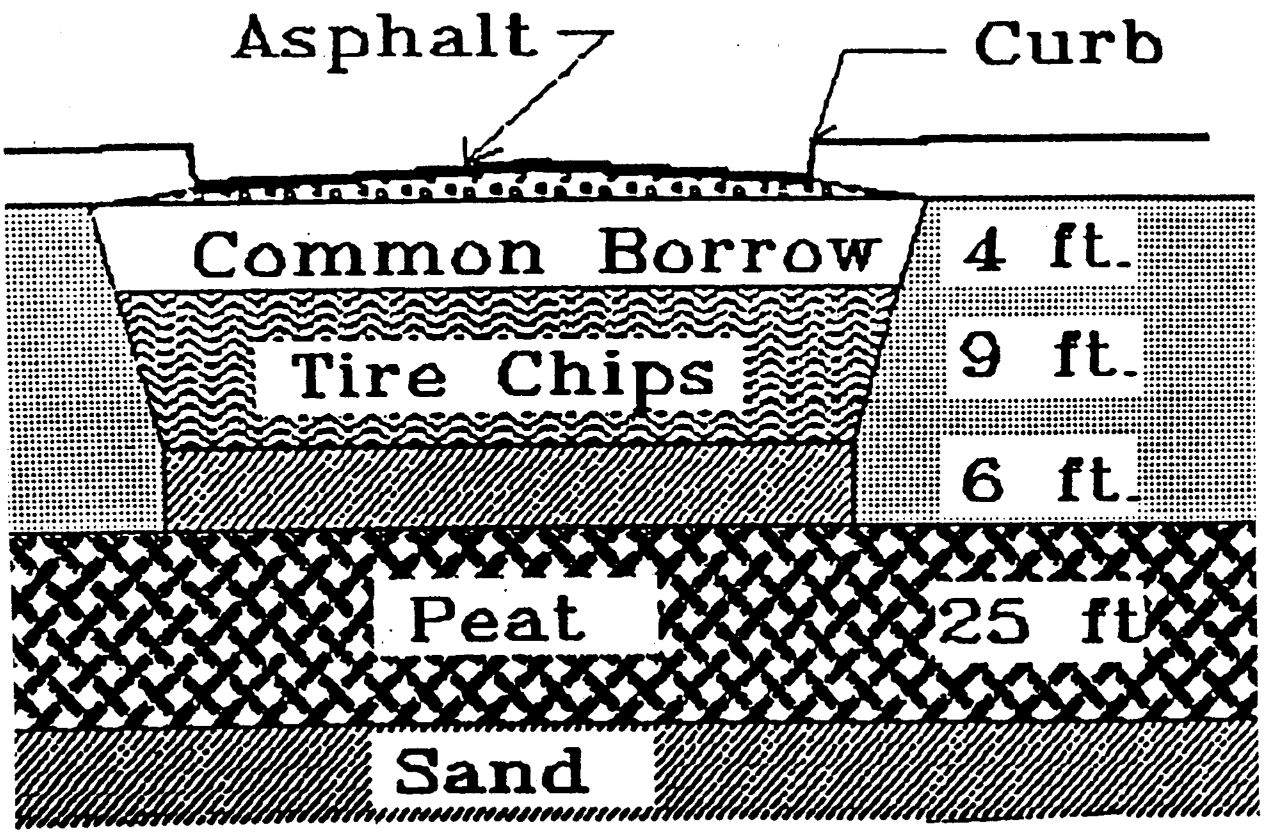


Fig. 14. Cross-section of Eden Prairie Road project [9].

2) With the use of shredded tires as lightweight fill material, the lighter embankment translates to less embankment settlement.
3) Placement of geotextile fabric followed by placement of an initial lift of shredded tires, reduce the risk of embankment shear failure into the weak organic soils.
4) The consolidation settlement of the shredded tires layer decreased with time (Fig.15 and 16). The final settlement of the shredded tires layer was on the average of about 2 ft.

Esker Trail Project

This project is a forest road located in Esker Trail, in Milaca, Minnesota [9]. On this project, it was necessary to traverse a 200 ft stretch of wetland to access a sand and gravel borrow. The subsoils consisted of very weak swamp deposits, on the order of 5 ft in thickness.

First State Tire, Inc supplied the shredded tires to this project. The size of shredded tires was about 6 to 8 in. in width and 12 to 24 in. in length.

A geotextile fabric was placed on the top of the 5-ft layer of peat. Next, a 3-ft layer of shredded tires was placed over the fabric with loaders, then the shredded tire layer was compacted with low ground pressure dozers. After that, another layer of geotextile fabric was placed to cap the compacted shredded tire layer. The geotextile fabric was covered with a 1.5-ft thick layer of common borrow soil. Upon completion of the common borrow soil placement, a 6-in. layer of granular material was placed. The cross-section of the embankment constructed is shown in Fig.17.

Field tests were conducted to determine the settlements of the peat and the shredded tire layer as a function of shredded tire subgrade, subbase, and base thicknesses. Two settlement plates were installed on the top of the first fabriclayer to monitor the displacements of the underlying peat due to overburden pressure. The settlement plates readings indicated that the total average

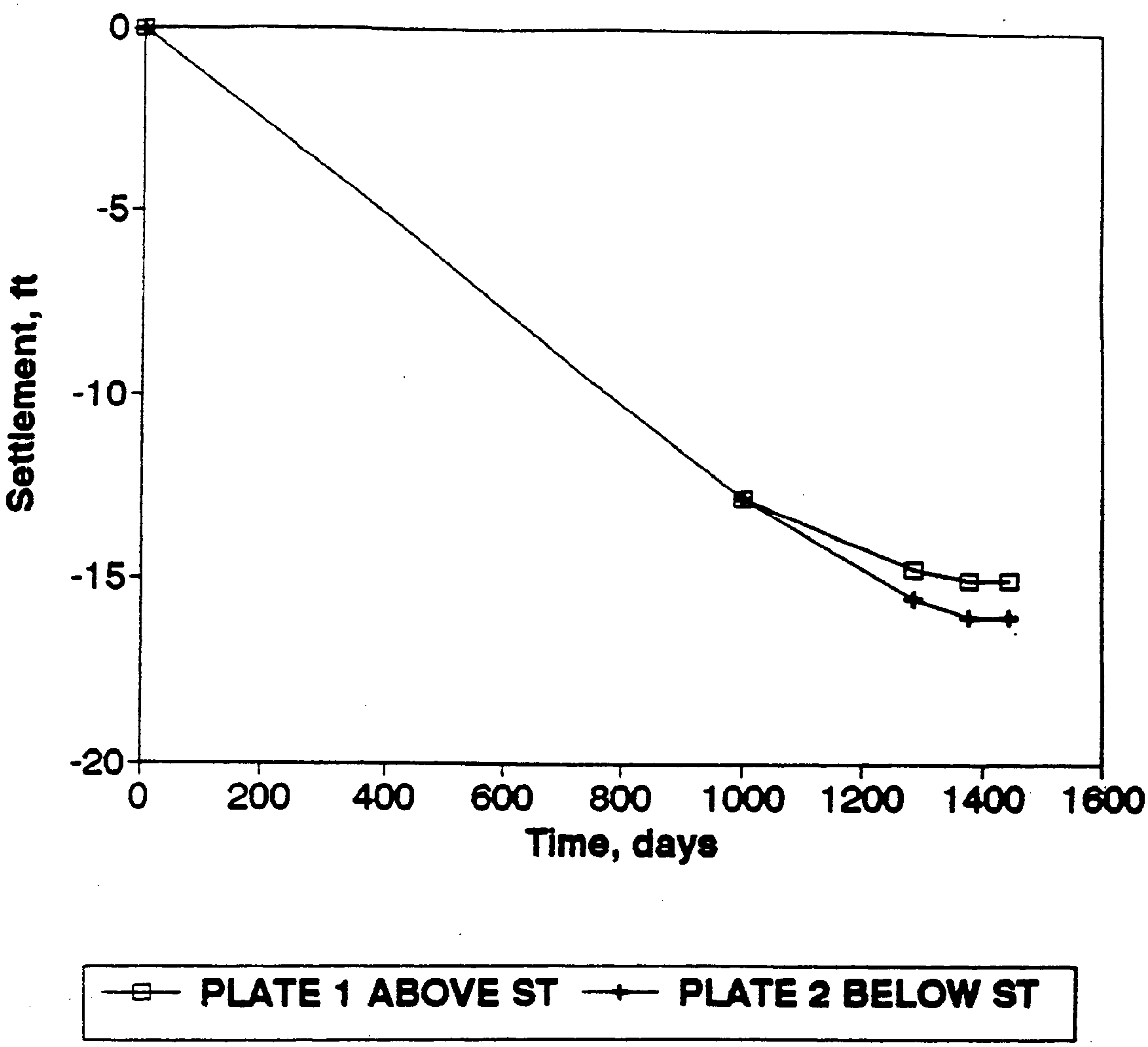


Fig. 15. Settlement of plates 1 and 2 for Eden Prairie project [9].

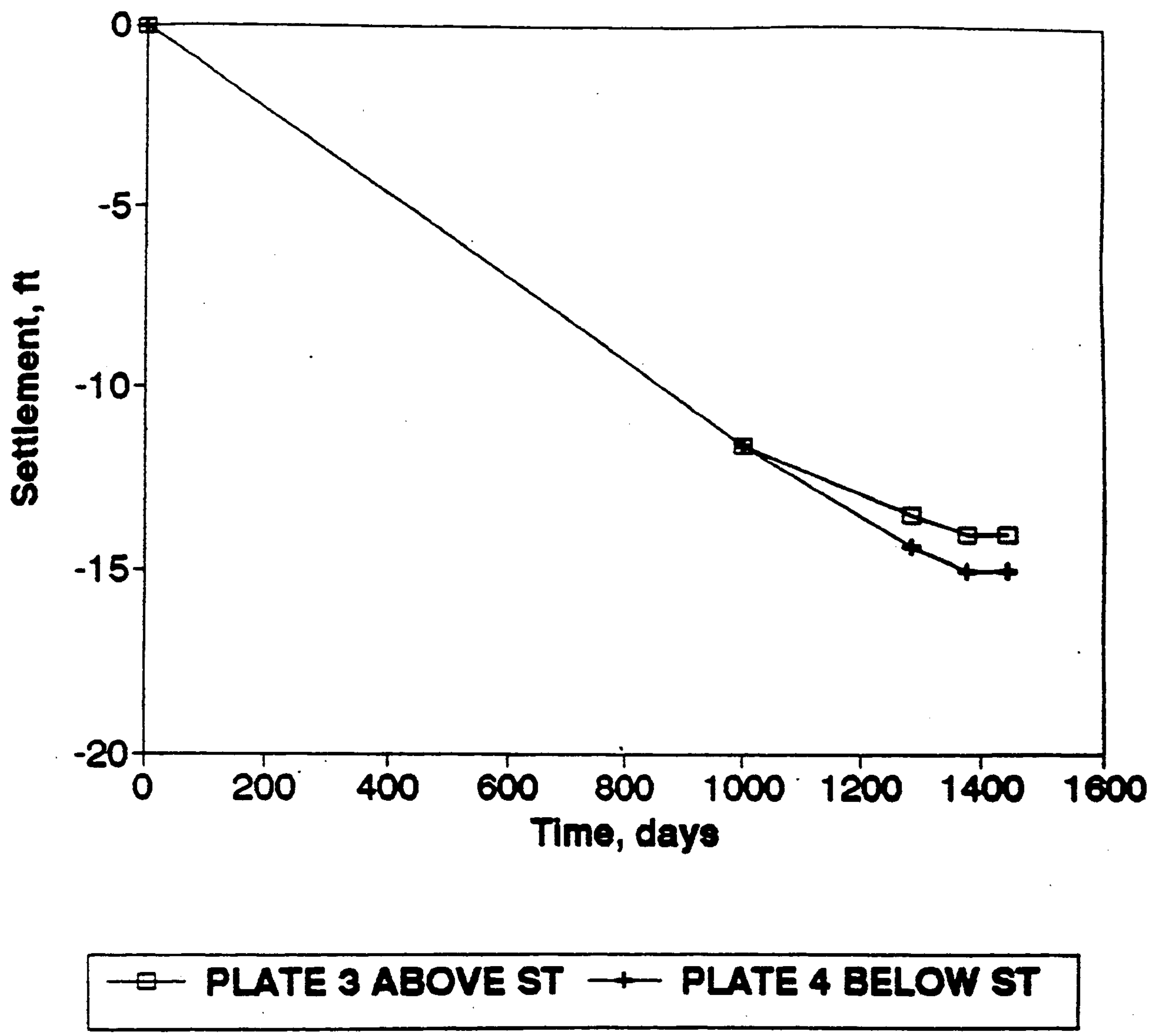


Fig. 16. Settlement of plates 3 and 4 for Eden Prairie project [9].

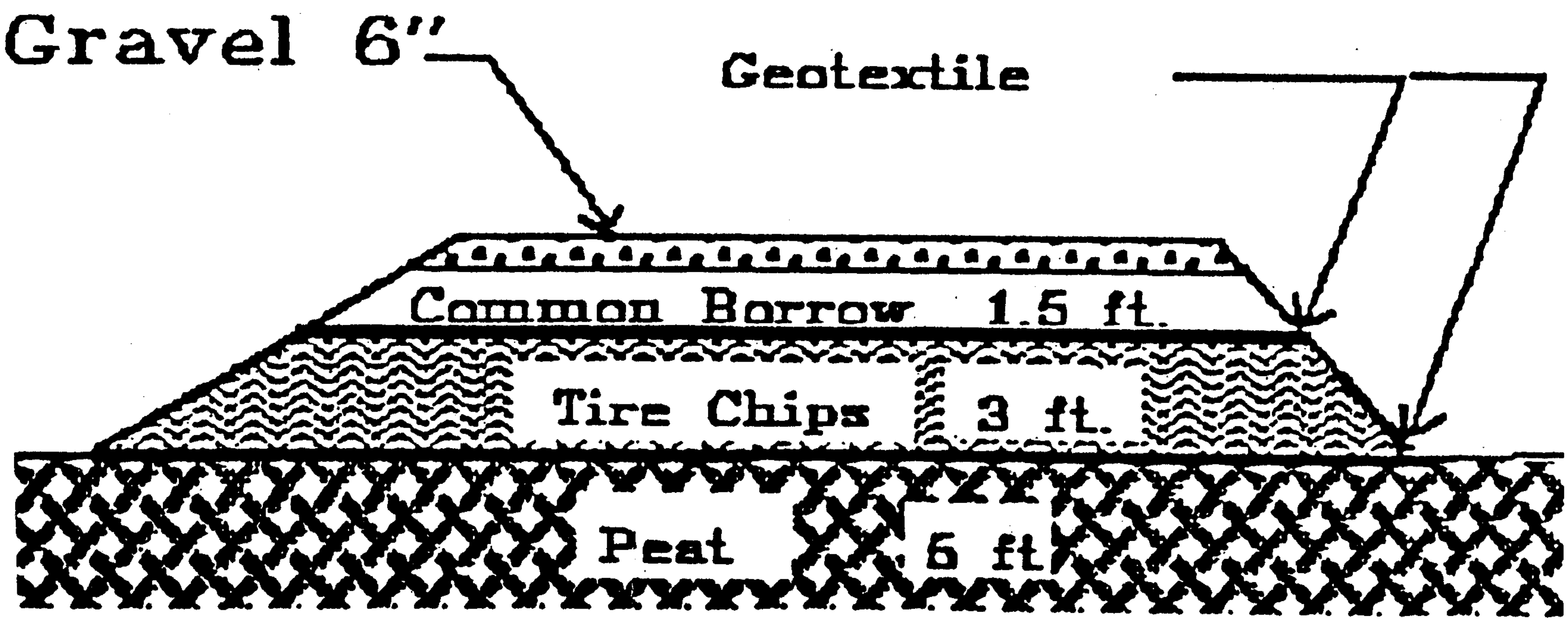


Fig. 17. Cross-section of the embankment on Esker Trail [9].

vertical deflection of embankment ranged from 0.75-1.25 ft. These displacement were approximately 40-50% less than what was anticipated with heavier mineral subgrade [9].

The total volume of shredded tires used in this project was about 27,000 ft^3. The estimated cost of producing 6 to 8 in. in width and 12 to 24 in. in length shredded tire pieces was $\$0.24/ft^3$. Therefore, the total cost of shredded tires was $6,480.

Based on the field test results, the following conclusions can be made:

1) The total deflection of the embankment constructed on weak subsoils with shredded tires subgrade is approximately 50% less than that of an embankment constructed with granular subgrade.
2) The fabric layer reduced the risk of shear failure of the weak strength soils.

Centerville Road Project

This project was initiated to reduce settlements of the Centerville Road south of County Road H-2, in Ramsey County, Minnesota [16]. It was determined that the desirable solution to avoid failure was to remove some of the existing material and replace it with lightweight fill such as shredded tires to reduce the load on the swamp deposits.

The site had deep deposits of swamp materials which were incapable of supporting the roadway. Construction of a surcharge fill started in 1989 to prepare the area for roadway construction. The initial fills caused failures in the swamp outside of the roadway area. The roadway cross-section is shown in Fig.18.

Maust Tire Recyclers, Inc. supplied the shredded tires to this project. The size of shredded tires used was 100% finer than 4 in. Shredded-tire placement began with an excavation to a point of 5 ft below the original roadway surface. Geotextile fabric was laid on the bottom of the excavation, and covered with a 3-ft layer of woodchips. Woodchips were placed to a depth 1 ft above the water table to ensure that the shredded tires did not come into contact with the water. Upon completion of the woodchip placement, a 5-ft layer of shredded tires

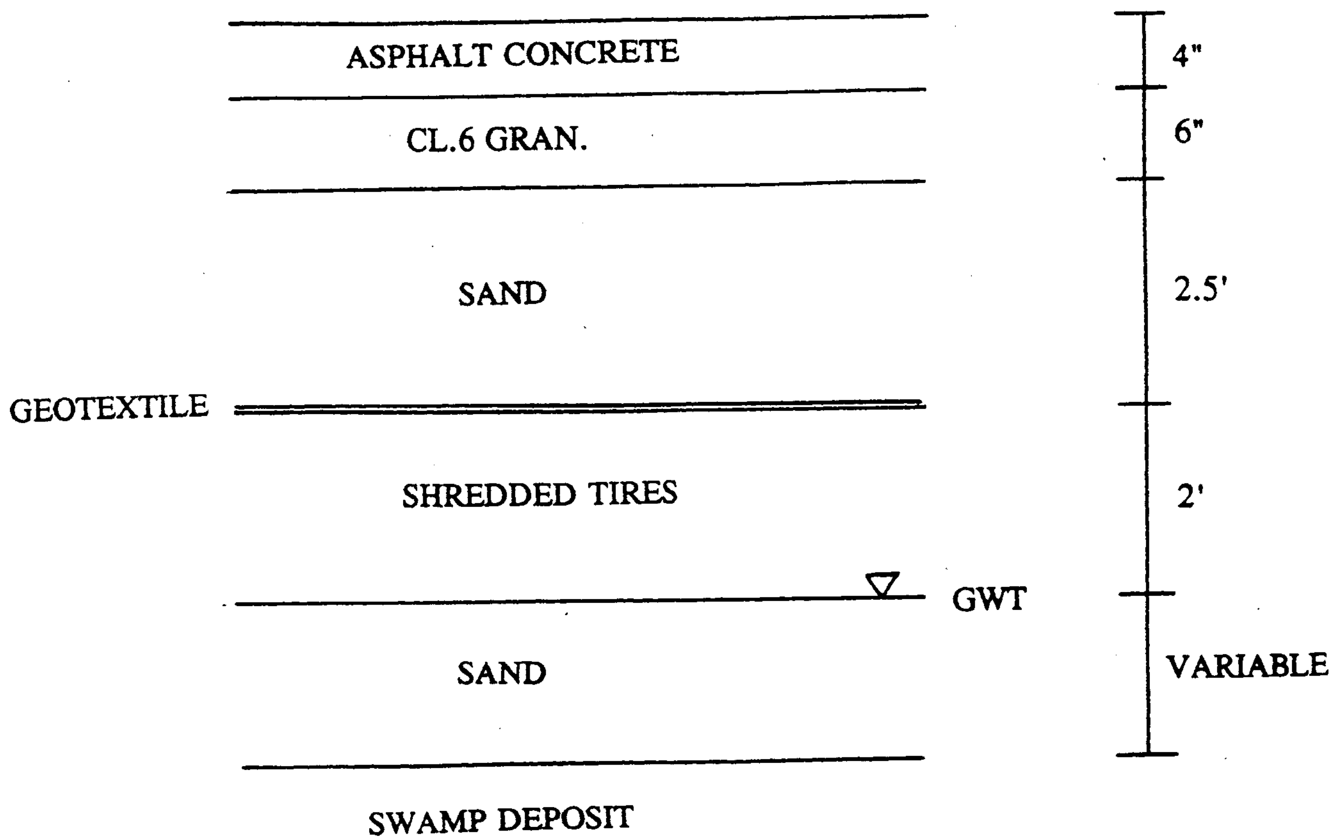


Fig. 18. Cross-section of Centerville Road project.

was placed on the top of woodchips. Next, the shredded tire layer was covered with another layer of fabric, and the two layers of fabric were sewn together to encapsulate the woodchip and shredded tire layer. This encapsulation was covered by 3 ft of granular material.

Due to the limited time to construct this project, no field tests were conducted to determine the physical and mechanical behavior of the shredded tires.

The estimated volume of shredded tires used in this project was about 67,500 ft^3. The cost of producing shredded tires 100% finer than 4 in. was about $0.074/$ft^3$. Therefore the total cost of shredded tires was $5,000.

The lack of field test made this project inconclusive from the engineering point of view. However, the size of the shredded tire pieces used in this project is similar to that of Prior Lake City project.

Minneapolis Convention Center Project

This project was located over the Convention Center's below-ground parking ramp, in downtown Minneapolis. In this project, the shredded tires were used as substitute for heavier material to reduce the weight on the parking ramp. The reduction in weight allowed the construction of a park above the ramp.

The subsurface consisted of slabs that form the roof of the below-ground parking ramp. Figure 19 shows the cross-section design of the park.

The source of shredded tires was First State Tire, Inc. The size of shredded tires was about 6 to 12 in. in length.

A geotextile fabric was laid on the top of the roof of the below-ground parking ramp. Next, a 3-ft layer of shredded tires was placed over the fabric by the loaders. The layer of shredded tires was then compacted with dozers. The compaction effort was considered satisfactory when the layer of shredded tires settled by approximately 30% of the total thickness. Another layer of fabric was placed on the top of the shredded tires, and covered with a 6 in. thick layer of sand which was compacted with a vibratory compactor.

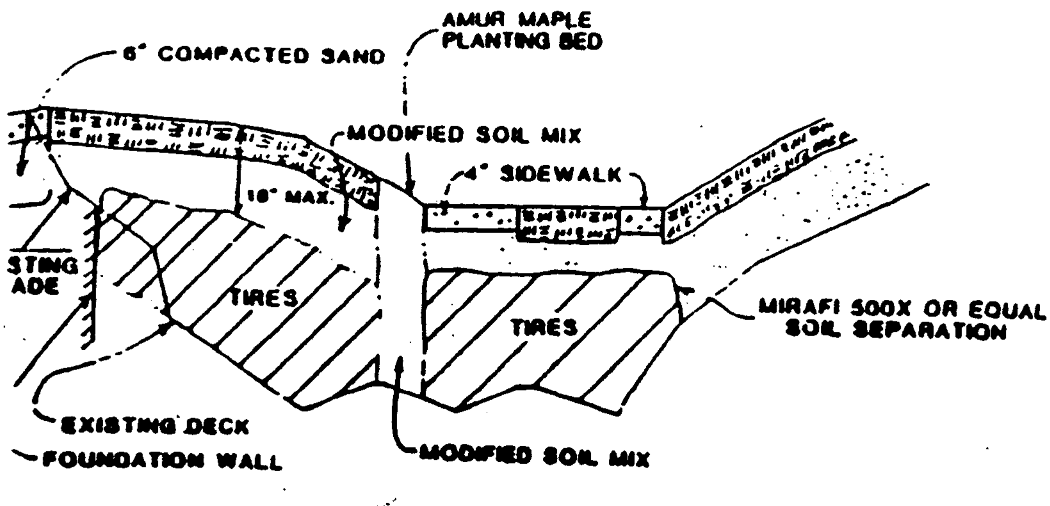


Fig. 19. Cross-section of Minneapolis Convention Center park.

No field tests were conducted to determine the physical and mechanical behavior of shredded tires.

The estimated volume of shredded tires used in this project was about 67,500 ft^3. The cost of reducing shredded tires to a size of 6 to 12 in. in length was about $0.13/$ft^3$. Therefore, the total cost of shredded tires was about $8,750.

Pine City Ramp Project

To prevent the reoccurence of a deep seated rotational failure in a plastic silty loam underneath a ramp on Interstate I-35 in Pine City, a lightweight fill was suggested. In 1992, a 15-ft depth of soil was excavated, lined with a Type 5 geotextile fabric, and filled with 30,000 yd^3 of shredded tires. The shredded tire pieces, with 90% passing 8 in. sieve, were placed in one-foot lifts, compacted with a dozer, and covered with Type 5 geotextile fabric. Settlement plates were installed for future deflection monitoring upon completion of the project in 1993.

CHAPTER 5

FIELD INVESTIGATION

INTRODUCTION

To provide access to a shredded tire stockpile from Pine County Road 5, G. Gotfredson decided to build an aggregate surface road with a shredded tire subgrade. This project was located at G. Gotfredson's tire dump near Mora, in Pine County, Minnesota.

The objective of this research project was to perform field tests on shredded tires.

SITE CHARACTERIZATION

The G. Gotfredson tire stockpile was situated on land previously used for growing corn and was covered with tall grass. Small patches of marshland spot the land as shown in Fig.20. The shredded tires were stored in two stockpiles 200 ft apart, which were located to the northeast of the road.

To characterize and classify the soil, auger samples were taken up to depth of 5 ft along the projected road. Visual inspection of the cores revealed about 1 ft of top soil, 1 ft of clay, and 1 ft of silty clay underlain by sand as shown in Fig.21. This sequence of soil types was fairly uniform along the road. The water table along the road was at a 5- to 6-ft depth.

Laboratory tests were conducted to determine the grain size distribution curve, Atterberg limits, and moisture content of the sand. Figure 22 shows the grain size distribution curve obtained from the sieve analysis. The liquid limit(Fig.23), plastic limit, and plasticity index were found to be: w=11%, LL=16.5%, PL=14.3%, PI=2.2%. According to the AASHTO Classification System, the sand was classified as group A-1-b.

The road was geometrically designed as shown in Figs.24 and 25.

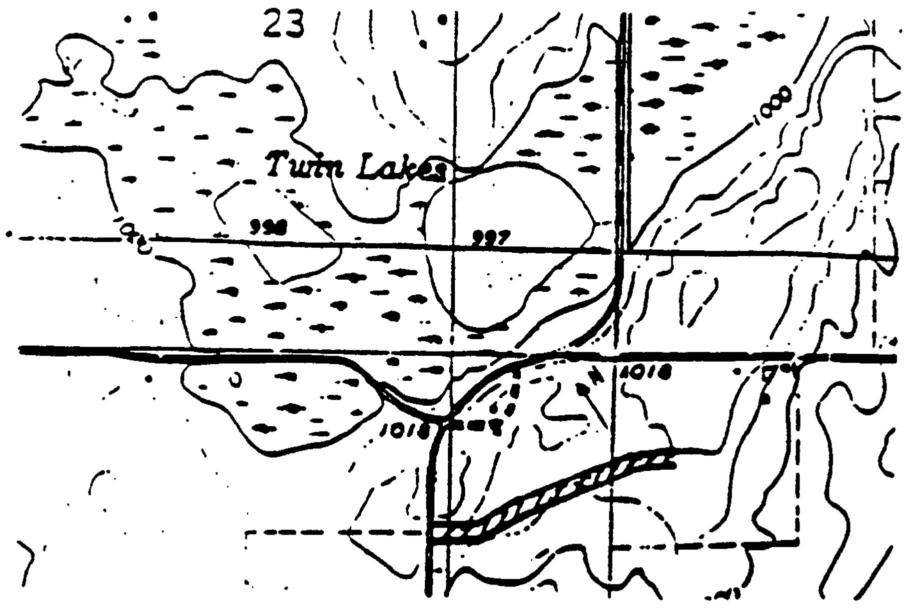


Fig. 20. Site location on Grasston Topographic Map.

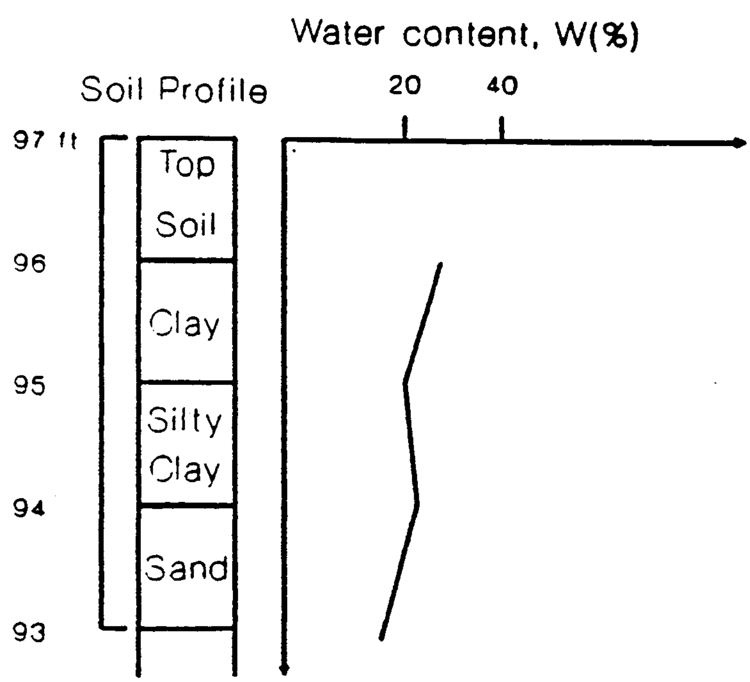


Fig. 21. Soil profile and variation of water content with depth.

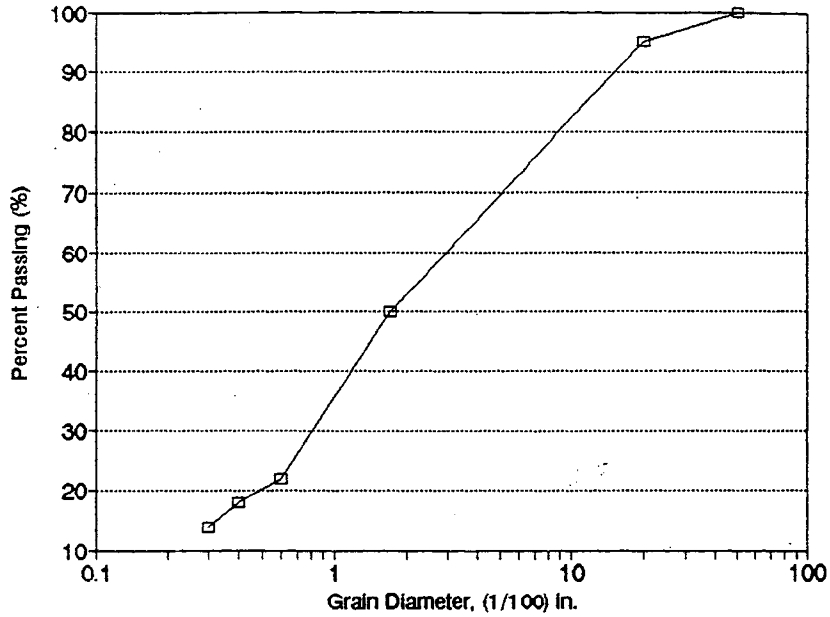


Fig. 22. Grain size distribution curve of sand.

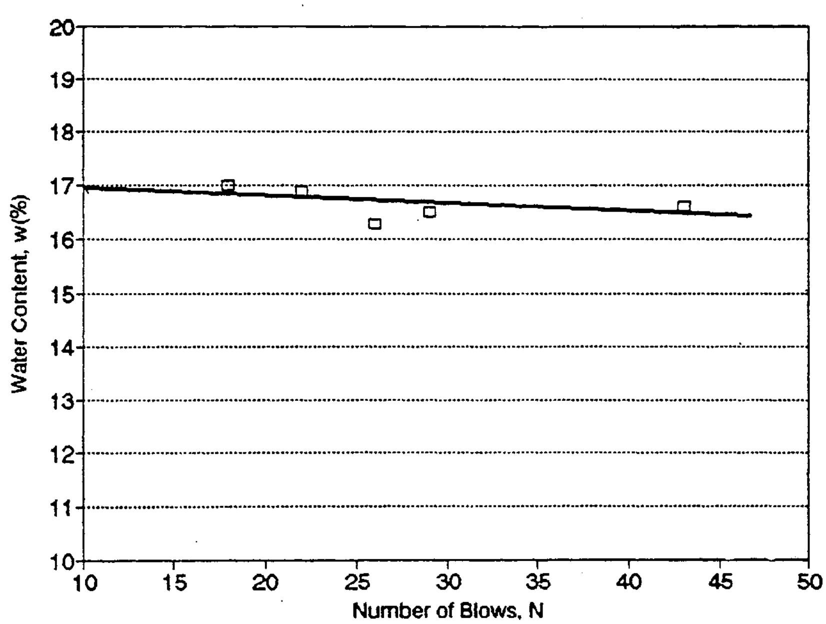


Fig. 23. Liquid limit and plastic limit of sand.

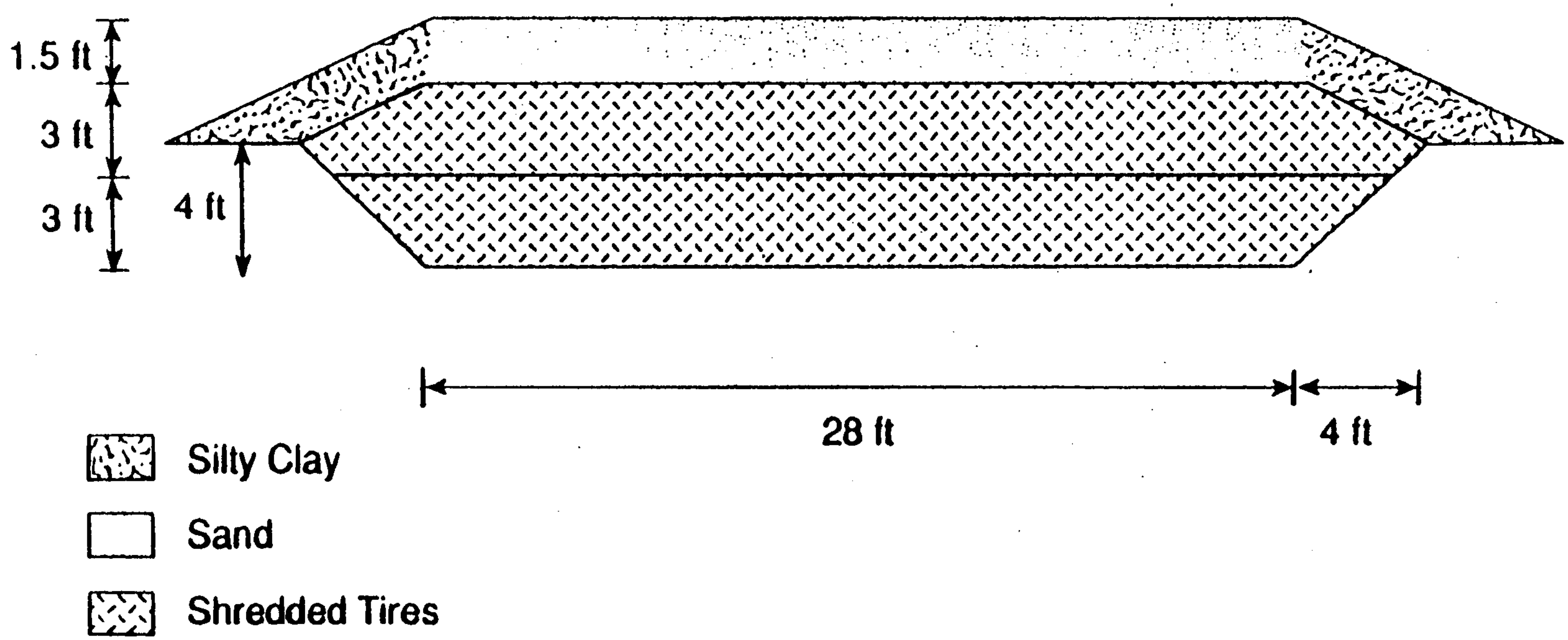


Fig. 24. Roadway cross-section of Sections A and C.

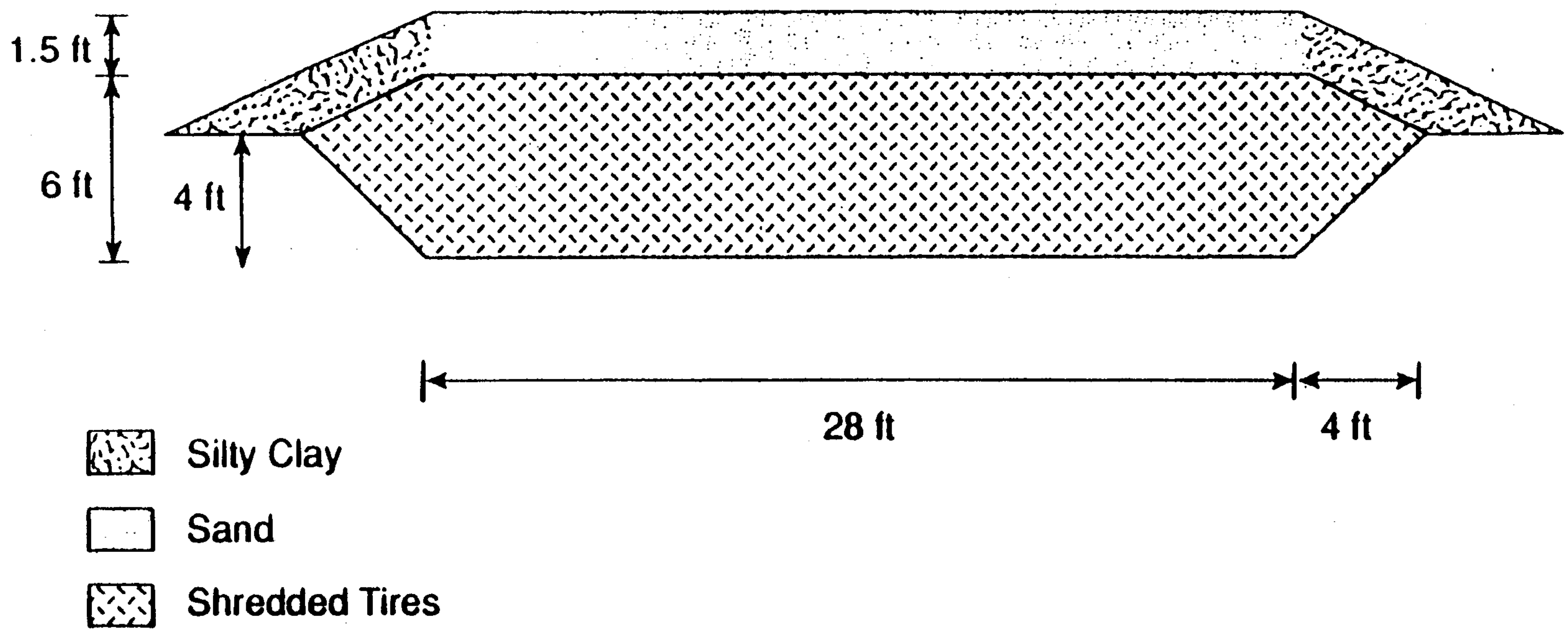


Fig. 25. Roadway cross-section of Sections B and D.

SHREDDED TIRES CHARACTERIZATION

A total of 400 pieces of steel-belted shredded tires were randomly collected from the two stockpiles. The length, width, and thickness of each piece was measured and documented. The average thickness of the pieces was approximately 1/2 in. Figure 26 shows the histogram of the aspect ratio of the shredded tires pieces. This figure shows that the aspect ratio distribution is skewed with an average of about 3.7. This skeweness is due to the nonuniformity of the shredded tires pieces

SHREDDED TIRES PLACEMENT

According to the road design (see Figs.24 and 25), the top soil and sand were excavated to a 4-ft depth along an area 724 ft long and 28 ft wide with a dozer. The top soil was placed on the north shoulder, and the sand on the south shoulder of the road. The elevation of the bottom of the excavation was then surveyed, and the four test sections were marked with stakes. Figure 27 shows the location of the four sections.

FIELD TESTS

The objective of field tests was to determine the settlements of the shredded tire subgrade as a function of subgrade thickness and compaction effort.

Four sections of the road, A, B, C, and D, were selected for controlled compaction as shown in Fig.27. Sections A and C were selected for the subgrade construction in two 3-ft thick layers. Sections C and D were selected for a 6-ft thick subgrade. A 27-ton Caterpillar D7F dozer was chosen for subgrade compaction. The compaction effort was quantified by the number of dozer passes over each layer.

Section A

A total of seven settlement plates with 7-ft long pipes were installed at the bottom of the excavation. The settlement plates were located at the edges of the road to reduce the risk of damage during shredded tire placement. The

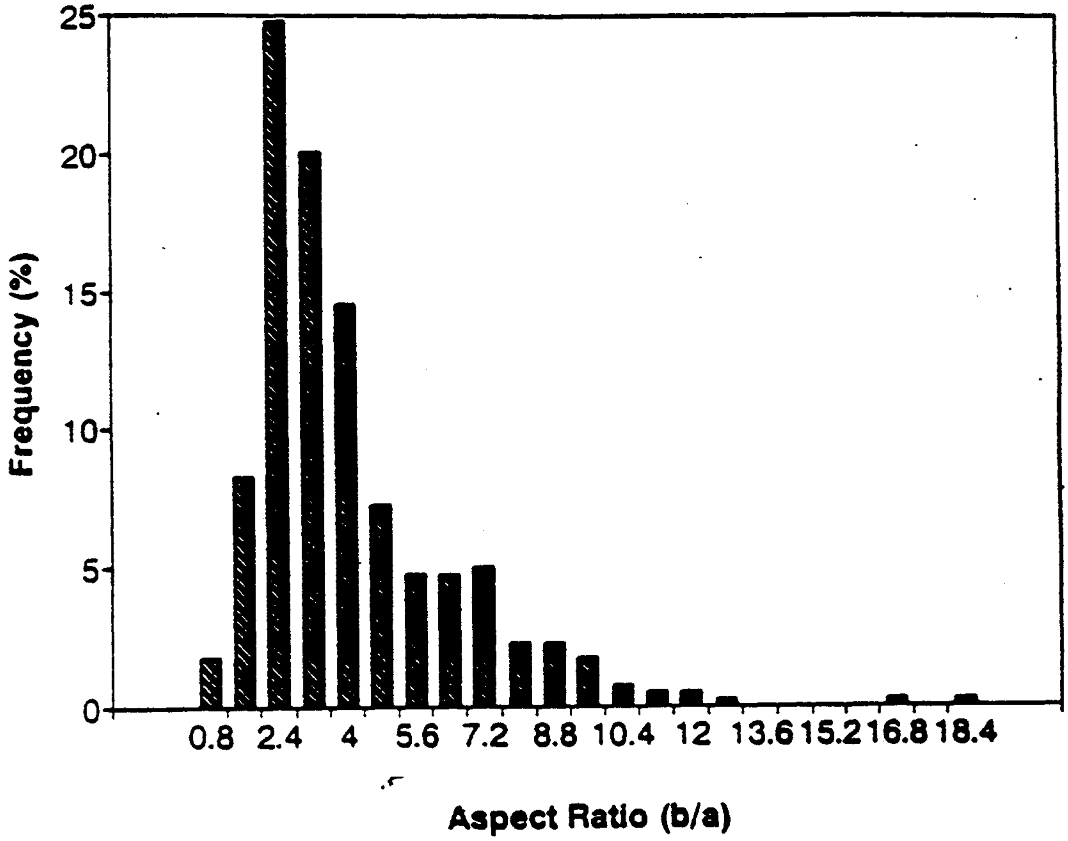


Fig. 26. Distribution of the aspect ratio of shredded tire pieces.

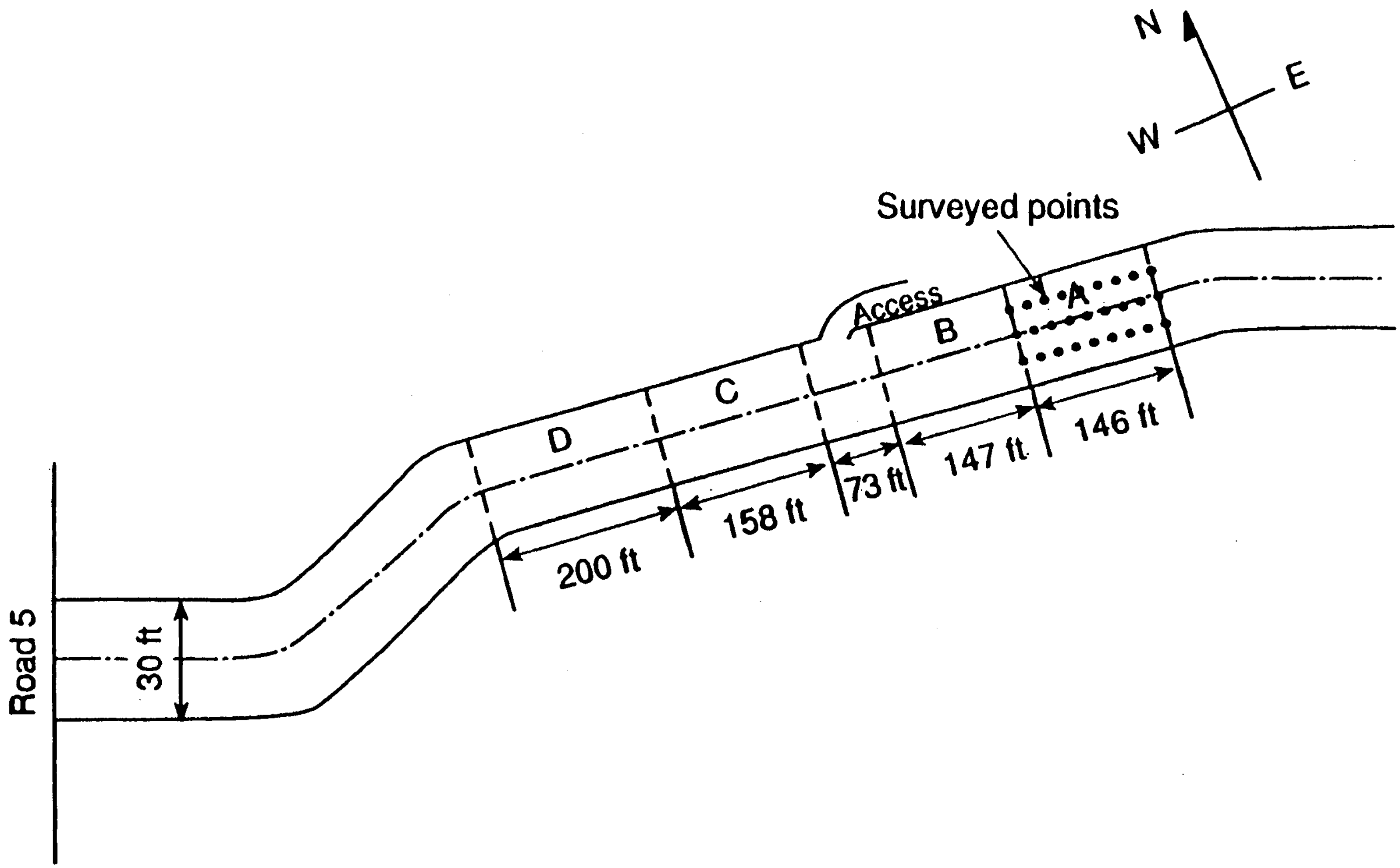


Fig. 27. Location of the four sections selected for study.

elevation of the top of the settlement plate pipes was measured with a Zeiss semi-automatic level and graduated rod.

A dump truck was used to fill the excavation with shredded tires. The lower 3-ft thick layer of shredded tires was constructed by slowly driving the dump truck with elevated bed over the base sand to produce the required thickness. A total of 12 truck loads were needed to construct the 3-ft shredded tire layer in Section A. After completion of the 3-ft shredded tire layer, its surface elevation was surveyed with the level and rod at a total of 27 points (see Fig.27). These points were located at 9 sectors, 18 ft apart along the road. At each sector 3 points were selected: 1 point was located at the middle of the sector and 2 points were located at an 8-ft distance on either side of the center point. These same points were used in surveying the elevation of the shredded tires surface during compaction.

Upon completion of the shredded tire layer, 4 Omega FT-T-20 thermocouple wires were embedded in shredded tire subgrade at 0, 1.5, 3, and 4.5 ft above the bottom of the excavation. Rubber hoses were used to protect the wires from damage. The ends of the wires were marked with different color tapes, and placed in a capped PVC vertical pipe located north of the road.

The shredded tires were compacted with the dozer rolling at 5 mph in 3 forth-and-back trips. Each trip was slightly offset to compact the whole width of the road. The 3 back and forth trips were counted as one pass. After 2, 8, 18, and 22 passes, the compaction was stopped and the elevation of the surface of the shredded tire layer was surveyed.

Upon completion of compaction, three settlement plates with 4 ft-pipes were placed next to the settlement plates with 7-ft pipes. A second layer of shredded tires, about 3-ft thick, was placed on the top of the compacted first layer and its surface elevation surveyed. The placement of shredded tires was done by slowly driving the dump truck with the elevated bed over the first layer. During this procedure, nearly all the settlement plate pipes were damaged by the truck. The compaction of the shredded tires was done in the same manner as for the first layer. Approximately 13 truck loads were placed on the top of the 3-ft shredded tire layer to construct the additional 3 ft shredded tires layer. The surface elevation surveying was done after 4, 8, and 12 passes.

Due to delays in constructing the road and approaching winter, no aggregate was placed on top of the shredded tire fill.

Sections B, C, and D

The first 3-ft layer of Section B was constructed simultaneously with that of Section A using the dump truck. The second layer of Section B was constructed using Gordfredson's front-loader driving on the first 3-ft shredded tire layer. The construction of Section B blocked the access to build Sections C and D. Therefore, to place shredded tires using the dump truck in Section C, an access road was constructed between the north shoulder of the road next to Section B and the bottom of the excavation using the dozer. In Section D, the shredded tires were placed on the north shoulder of the road by the dump truck. After that, the shredded tires were pushed by a front-loader into this section. Sections B, C, and D, were not compacted, however, due to equipment failure and weather related delays.

DATA ANALYSIS

Since no compaction was performed for Sections B, C, and D, only the results for Section A are presented below. Also, due to the damage of settlement plates, only surveying results were used for evaluating compaction.

Using the surface elevation data, graphs were developed showing the shape of the shredded tires surface as a function of the number of dozer passes and the thickness of shredded tires. Figures 28 through 33 depict the elevation (profile) of the 3 ft shredded tires layer in sectors 1-6 as a function of the number of dozer passes. A similar dependence when the additional 3 ft of shredded tires were placed on the top of the first 3-ft layer is shown in Figs. 34 through 39.

According to field observations, the elevation of the north and the south edge of each sector was assumed to be equal to the elevation of the middle point

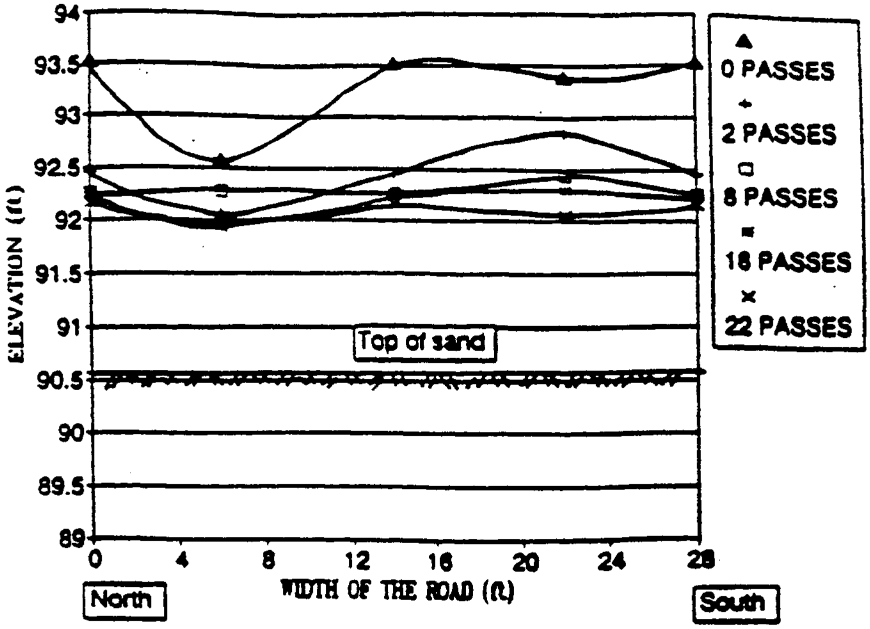


Fig. 28. Profile of the 3-ft shredded tire layer in Sector 1.

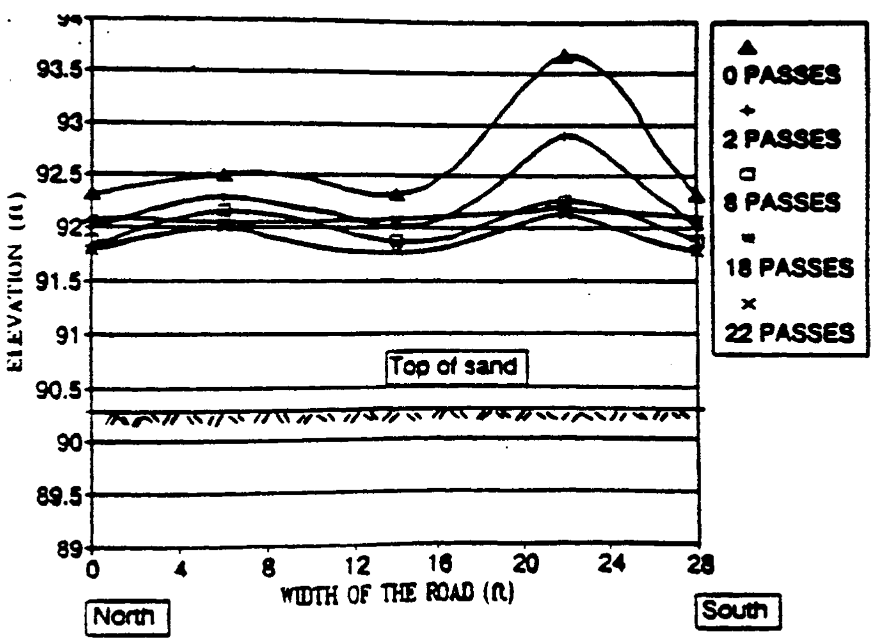


Fig. 29. Profile of the 3-ft shredded tire layer in Sector 2.

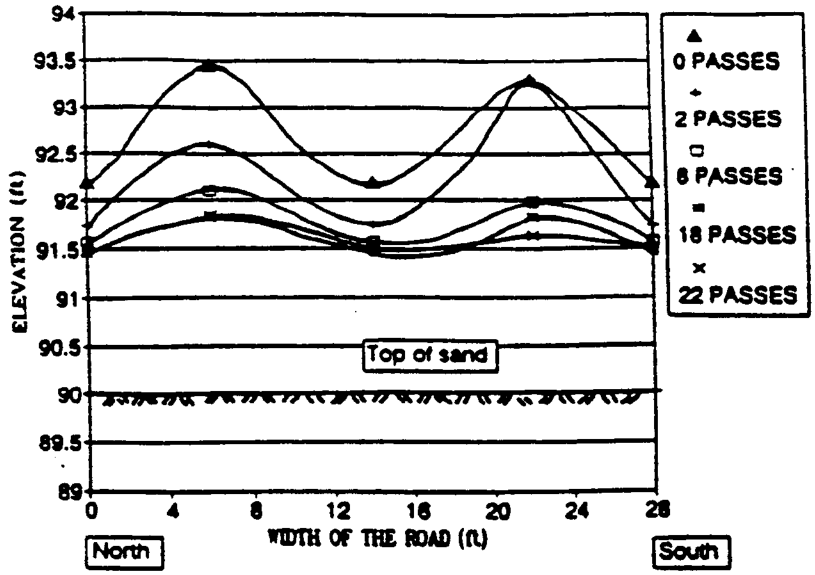


Fig. 30. Profile of the 3-ft shredded tire layer in Sector 3.

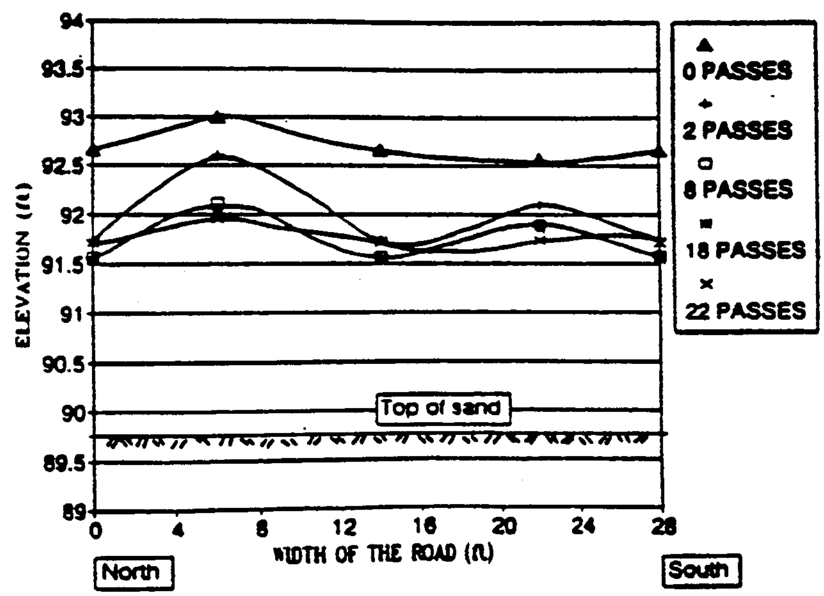


Fig. 31. Profile of the 3-ft shredded tire layer in Sector 4.

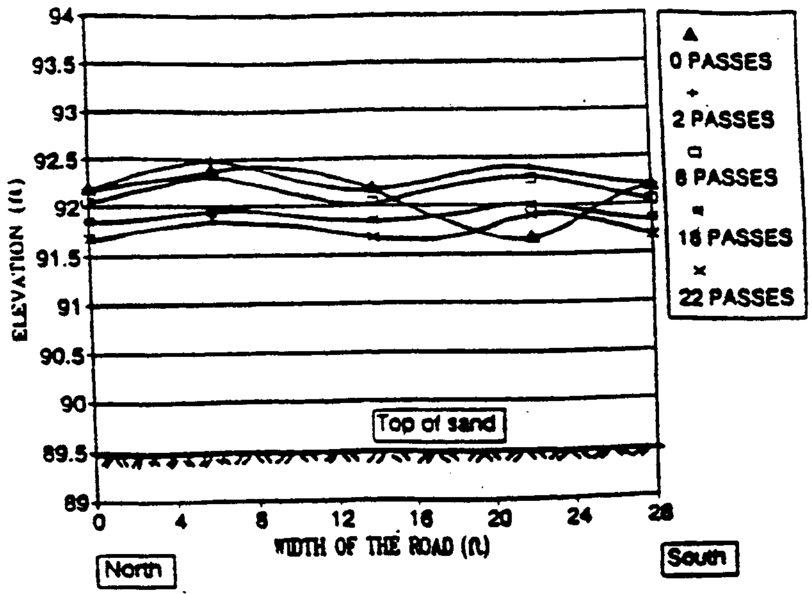


Fig. 32. Profile of the 3-ft shredded tire layer in Sector 5.

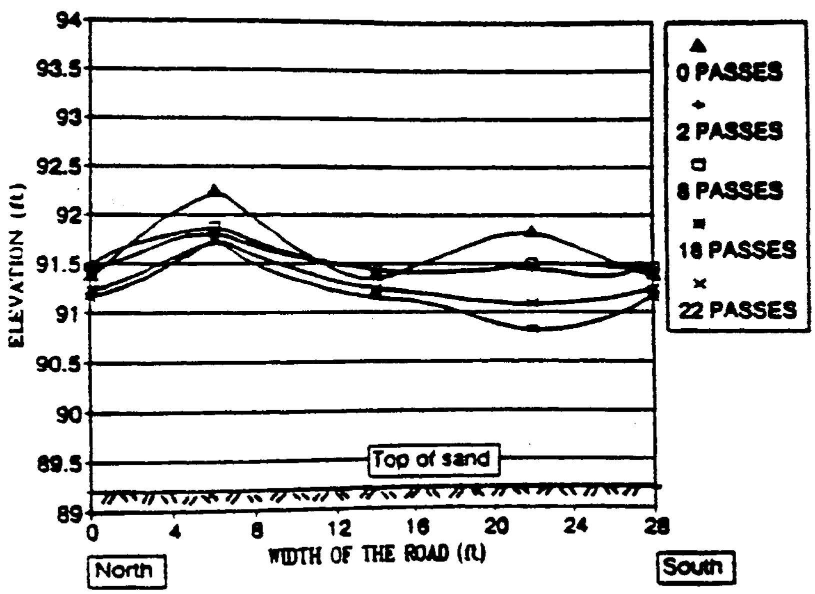


Fig. 33. Profile of the 3-ft shredded tire layer in Sector 6.

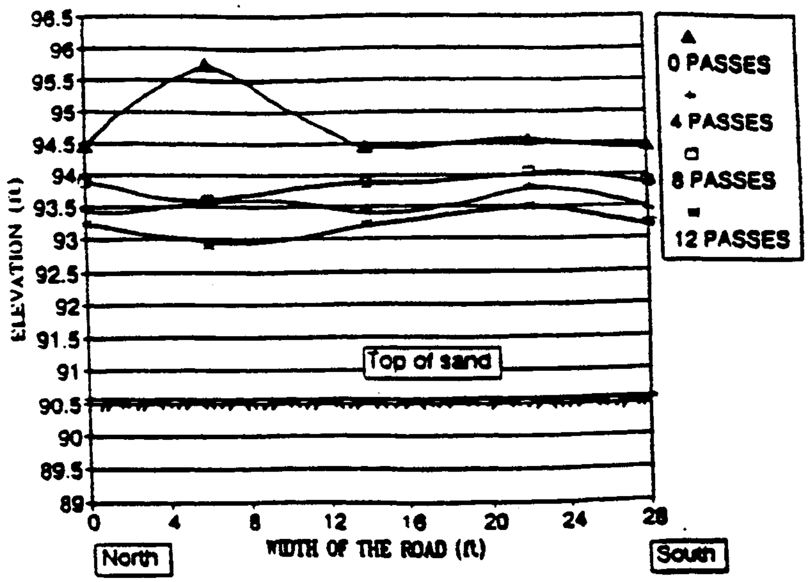


Fig. 34. Profile of the 3+3-ft shredded tire layer in Sector 1.

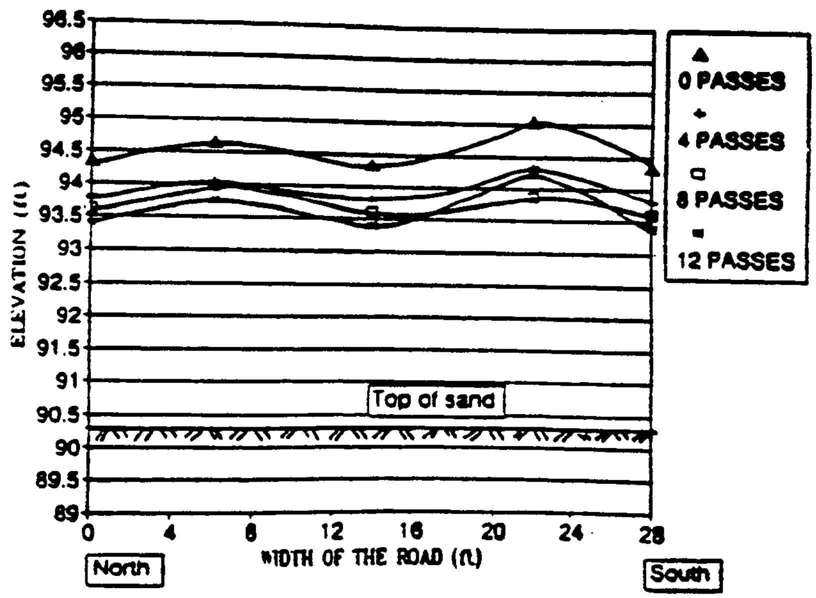


Fig. 35. Profile of the 3+3-ft shredded tire layer in Sector 2.

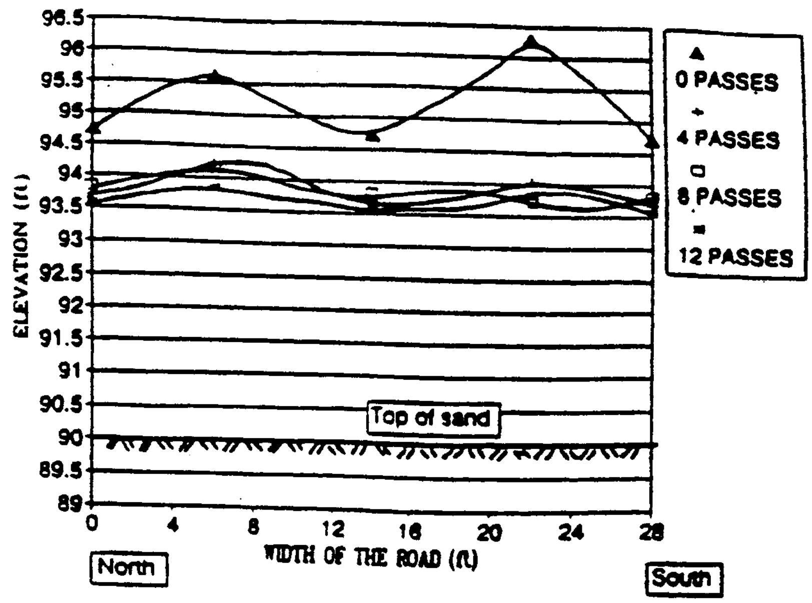


Fig. 36. Profile of the 3+3-ft shredded tire layer in Sector 3.

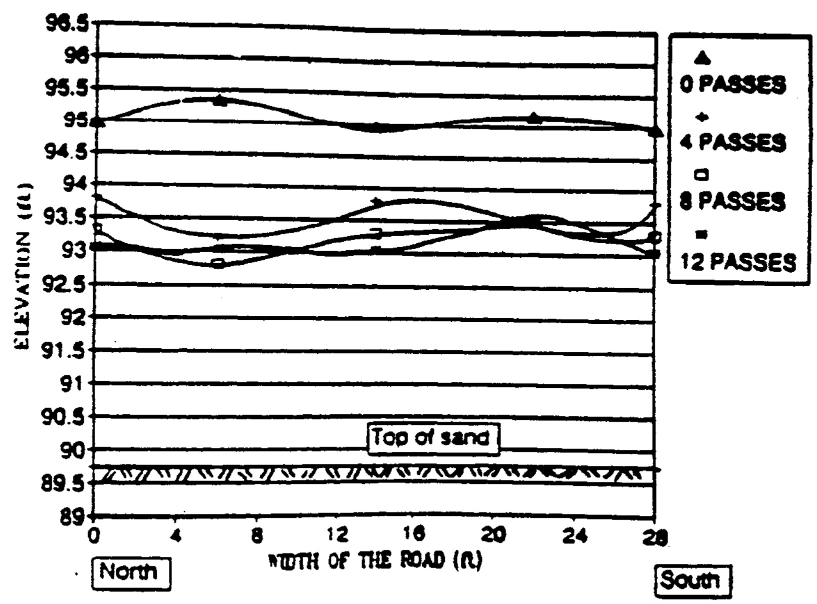


Fig. 37. Profile of the 3+3-ft shredded tire layer in Sector 4.

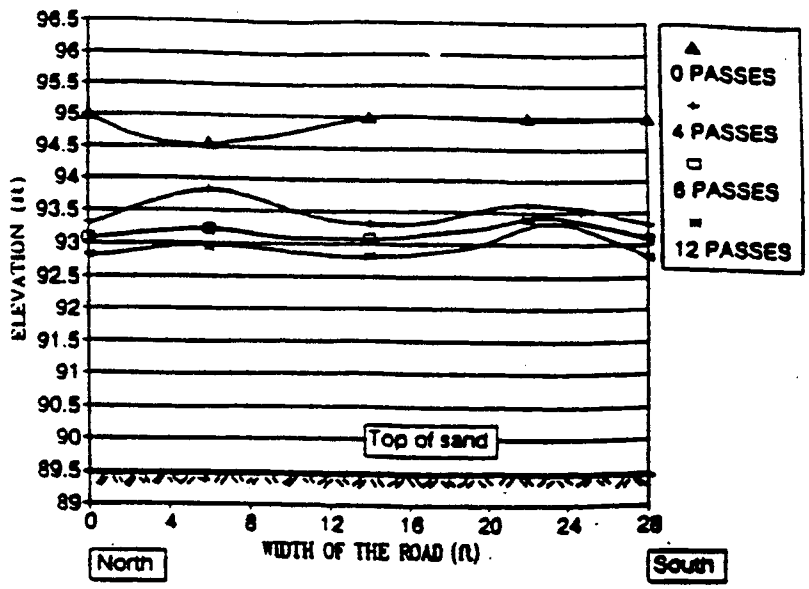


Fig. 38. Profile of the 3+3-ft shredded tire layer in Sector 5.

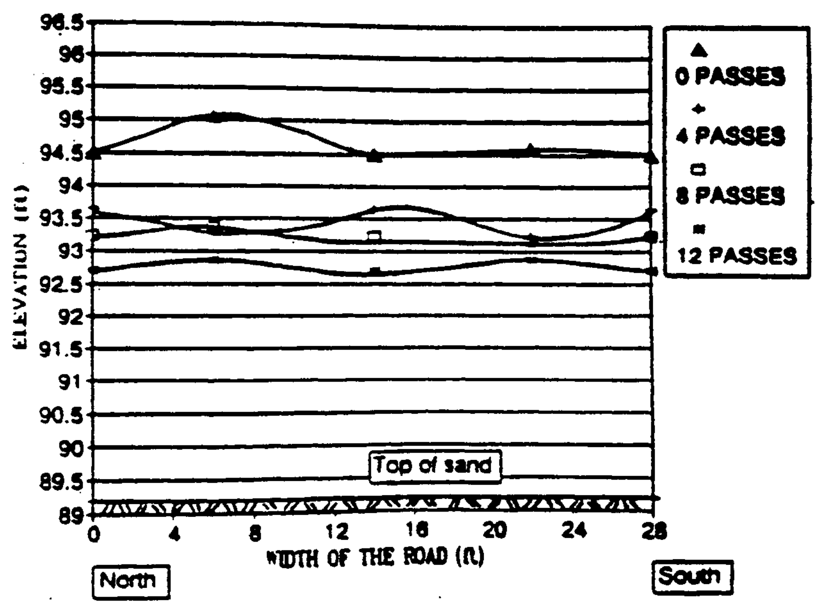


Fig. 39. Profile of the 3+3-ft shredded tire layer in Sector 6.

of the sector. Figure 40 shows initial and after compaction profiles of Section A along the length of the road. The dependence of the average displacement of Section A on the number of dozer passes is shown in Fig.41. The number of effective passes for 3-ft layer and the 3+3-ft layer was about 15 passes.

From the average displacements, the average vertical strains ϵ_v were calculated from

$$\epsilon_v = \frac{\Delta H}{H_o} \tag{1}$$

where ΔH is the average displacement, and H_o is the initial average thickness. The results as a function of dozer passes are shown in Figure 42. This figure shows that the 3-ft layer and 3+3 ft layer did not settle more than 30% and 37% of the initial average thickness, respectively.

Since the road was not covered by an aggregate, no temperature measurements were taken during the winter of 1990/91.

COST ANALYSIS

The cost of shredded tires of this project was not established because the shredded tire material was provided locally by G. Gotfreyson's tire dump.

CONCLUSIONS

Based on the field tests conducted on Section A, the following conclusions were reached:

1) A loosely placed shredded tire subgrade consisting of large pieces can be easily compacted with a dozer. However, construction equipment regularly suffered damage to hydraulic systems substantially decreasing the efficiency of the construction.
2) For the same number of dozer passes, the rate of compaction of the 3-ft shredded tire layer is smaller than that of the 3+3-ft layer.

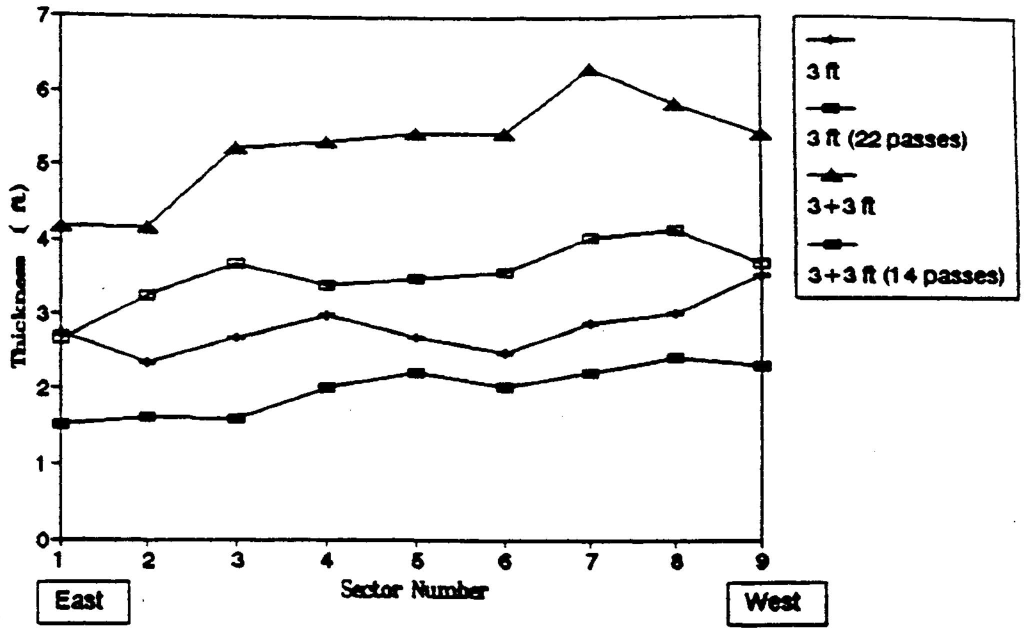


Fig. 40. Initial and after compaction profiles for the 3-ft and 3+3-ft sections.

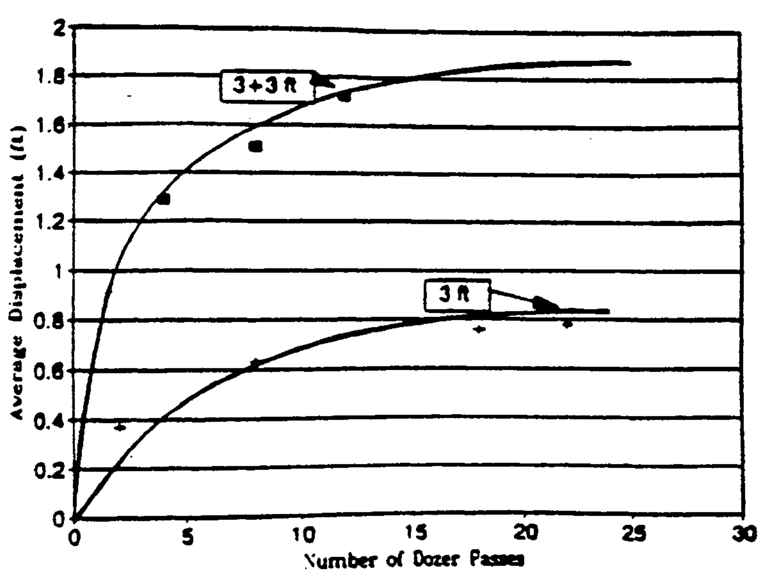


Fig. 41. Average displacemen versus number of dozer passes.

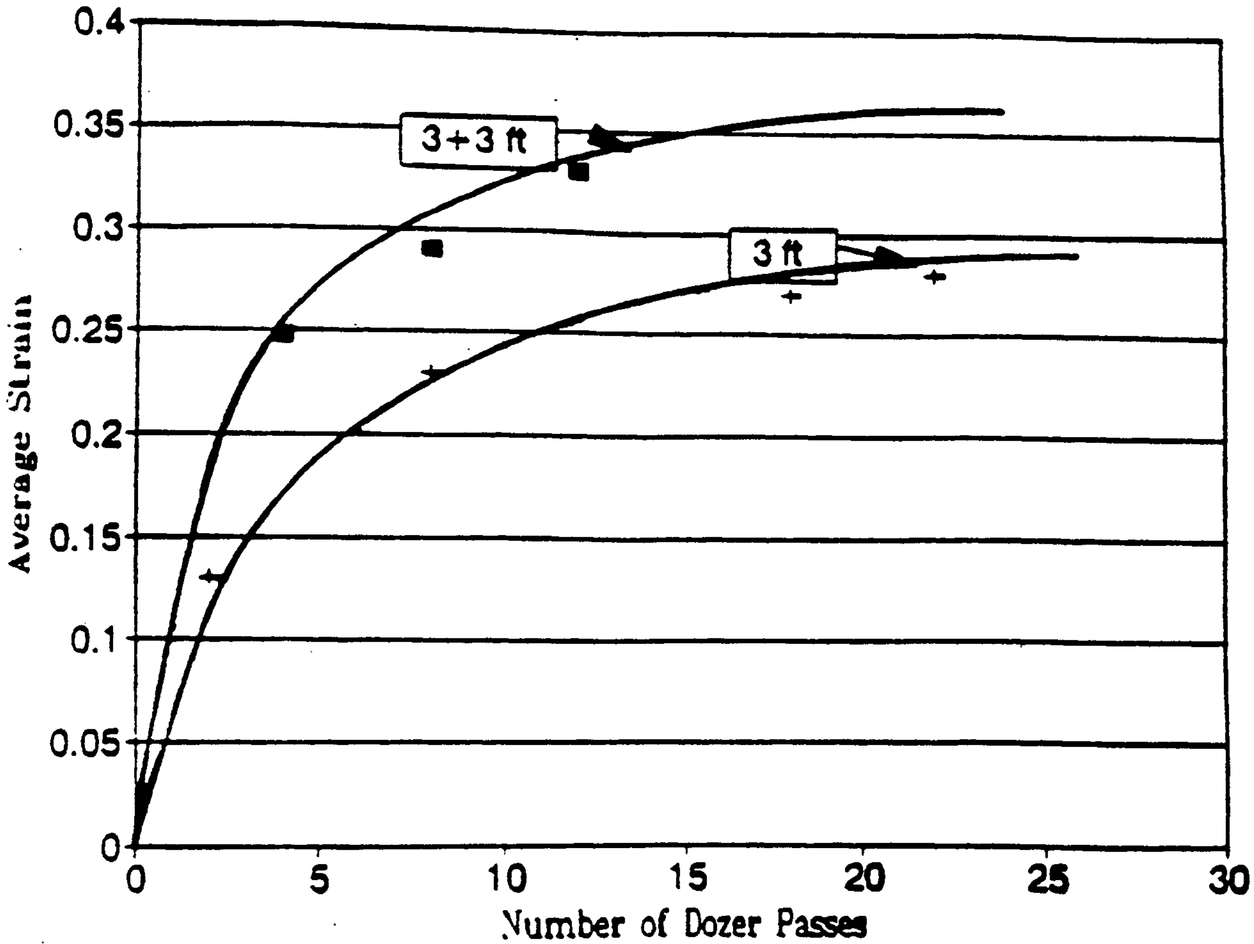


Fig. 42. Average strain versus number of dozer passes.

3) The rate of increase of the average displacement of the 3-ft and 3+3-ft layers decreases gradually with the number of dozer passes.

4) The rate of increase of the average strain of the 3-ft and 3+3-ft layers decreases gradually with the number of dozer passes.

5) The rate of increase of the bulk unit weight of the 3-ft and 3+3-ft layer decreases gradually with the number of dozer passes.

6) A 99% level of the compaction was accomplished with about 24 passes for either the 3-ft or the 3+3-ft layer.

7) The number of passes for effective compaction of a 3-ft and a 3+3-ft layers is about 15 passes.

8) Settlement plates can be easily damaged during either the placement of the shredded tires or their compaction. The settlements of the shredded tire layer can be adequately measured by means of surveying.

CHAPTER 6

SHREDDED TIRES PHYSICAL AND MECHANICAL PROPERTIES

The evaluation of certain physical and mechanical properties of shredded tires is described in this chapter. The first part describes the objective and scope of the proposed laboratory tests. The second explains the evaluation of certain physical parameters, and the third gives the mechanical parameters of shredded tires. The last part describes the laboratory tests.

INTRODUCTION

There are few attempts reported in the literature to evaluate the physical and mechanical properties of shredded tires. They were limited to the evaluation of gradation, bulk unit weight, specific gravity, permeability, cohesion and the internal friction angle. These attempts are presented and summarized in the sections below.

The objective of the laboratory tests at the University of Minnesota was to determine the compressibilty and elastic parameters of the shredded tires and woodchips that have been already used as lightweight fill material. To accomplish this objective, a series of one-dimensional compressibility laboratory tests were conducted on large specimens of shredded tires and woodchips. The results of the laboratory and analytical study of the engineering properties of the shredded tires may serve as a reference for use of shredded tires in highway construction.

PHYSICAL PARAMETERS

Gradation Analysis

CalTrans conducted a gradation analysis on two types of small size shredded tires [11]. The first type which was produced from truck tires, consisted of pieces greater than 2 in. and less than 3 in. The other type which was produced from passenger tires, contained smaller pieces. These two types were referred to as " 2 in. square" and "2 in. shredded", respectively. The corresponding size distribution curves are shown in Figs.6 and 7, respectively. The particle area distribution (histogram) of large size shredded tires used in G. Gotfredson's project is shown in Fig.43, and the particle area distribution curve is shown in Fig.44. Figure 43 shows that the average particle area of shredded tires was about 144 in^2.

Bulk Unit Weight

CalTrans conducted maximum/minimum bulk unit weight test on two types of of small size shredded tires described above [11]. The minimum bulk unit weight was found to be about 27.3 lb/ft^3 for the 2 in. square and 25.6 lb/ft^3 for the 2 in. shredded tires. The maximum bulk unit weight was found to be about 31.4 lb/ft^3 and 35.3 lb/ft^3 for the 2 in. square and the 2 in. shredded, respectively. Unfortunately, no details are presented in [11] on the methodology of conducting maximum/minimum bulk unit weight test.

The specific gravity of these two types of shredded tires was determined using ASTM C127 procedure. The specific gravity was found to be 1.15 for the 2 in. square and 1.06 for the 2 in. shredded tires.

Information on unit weight was also obtained from field tests inGotfredson's project. The bulk unit weight was determined using a dump truck. First, the empty truck was weighed at the weigh station located at Grasston. Next, the bed of the dump truck, with dimensions 19.5 ft by 10.5 ft by 4.5 ft, was filled up to 4.5 ft with shredded tires and the truck was weighed at the weigh station. This procedure was repeated six times, each time using new bulk of shredded tires. The average uncompacted bulk unit weight of shredded tires was calculated from

$$\gamma_{to} = \frac{W_{ts} - W_t}{V} \qquad (2)$$

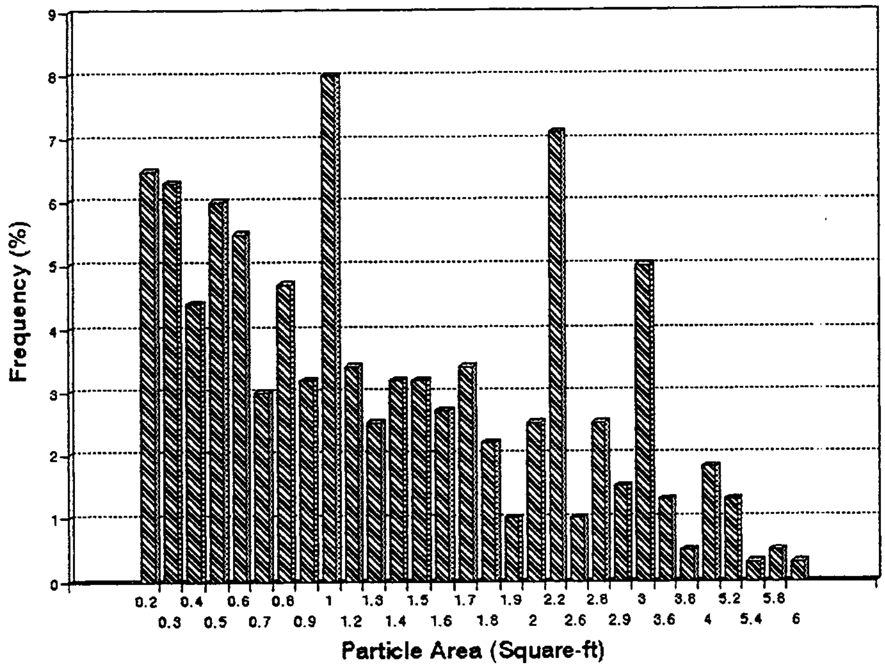


Fig. 43. Distribution of particle area of shredded tires.

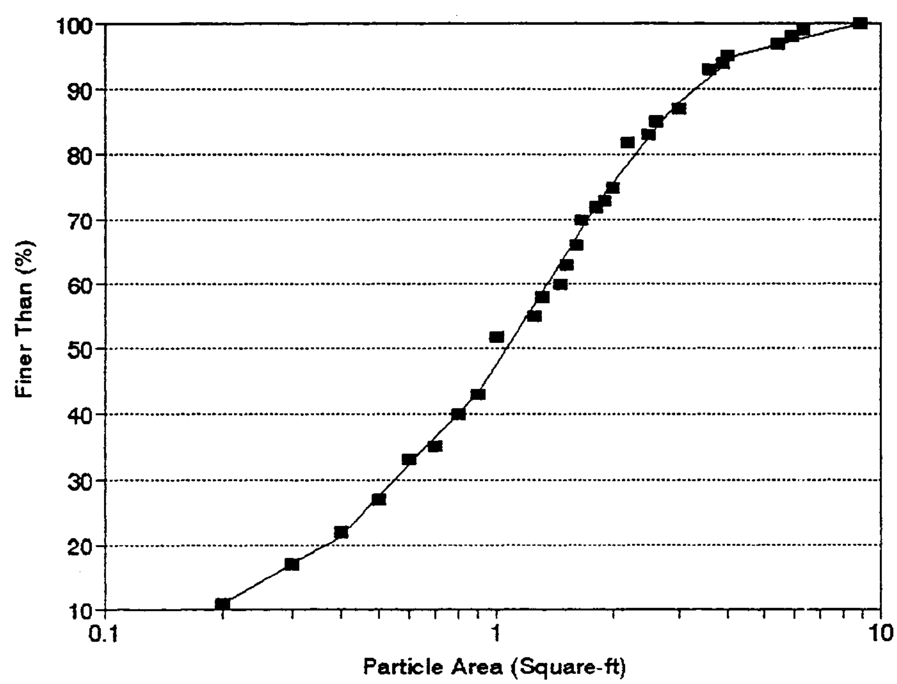


Fig. 44. Cumulative distribution curve of particle area of shredded tires.

where γ_{to} is the uncompacted bulk unit weight, W_{ts} is the average weight of the truck filled with shredded tires, W_t is the average weight of empty truck, and V is the average volume of the bed filled with shredded tires. With W_{ts}=31,000 lb, W_t=17,680 lb, and V=921.38 ft^3, the average uncompacted bulk unit weight is 14.5 lb/ft^3.

The average compacted bulk unit weight was calculated from the following expression

$$\gamma_t = \gamma_{to} \frac{H_o}{H_o - \Delta H} \tag{3}$$

where H_o is the average initial thickness of the shredded tire layer, and ΔH is the average displacement. Figure 45 shows the dependence of the bulk unit weight after compaction on the number of dozer passes. The maximum compacted bulk unit weight after 24 D7F-dozer passes for the 3-ft layer and the 3+3-ft layer was about 22 lb/ft^3. This figure was based on the assumption that 3+3-ft layer has an uncompacted bulk unit weight equal to that of the 3-ft layer.

Permeability Coefficient

CalTrans conducted a constant head permeability test on the two types of shredded tires described before. The permeability coefficients of the two types of shredded tires were within the order of magnitude, 10,000 ft/day [11].

Porosity

From the results of the tests conducted by CalTrans [11], the porosity can be estimated from the following equation

$$\gamma_t = (1 - n) G_s \gamma_w \tag{4}$$

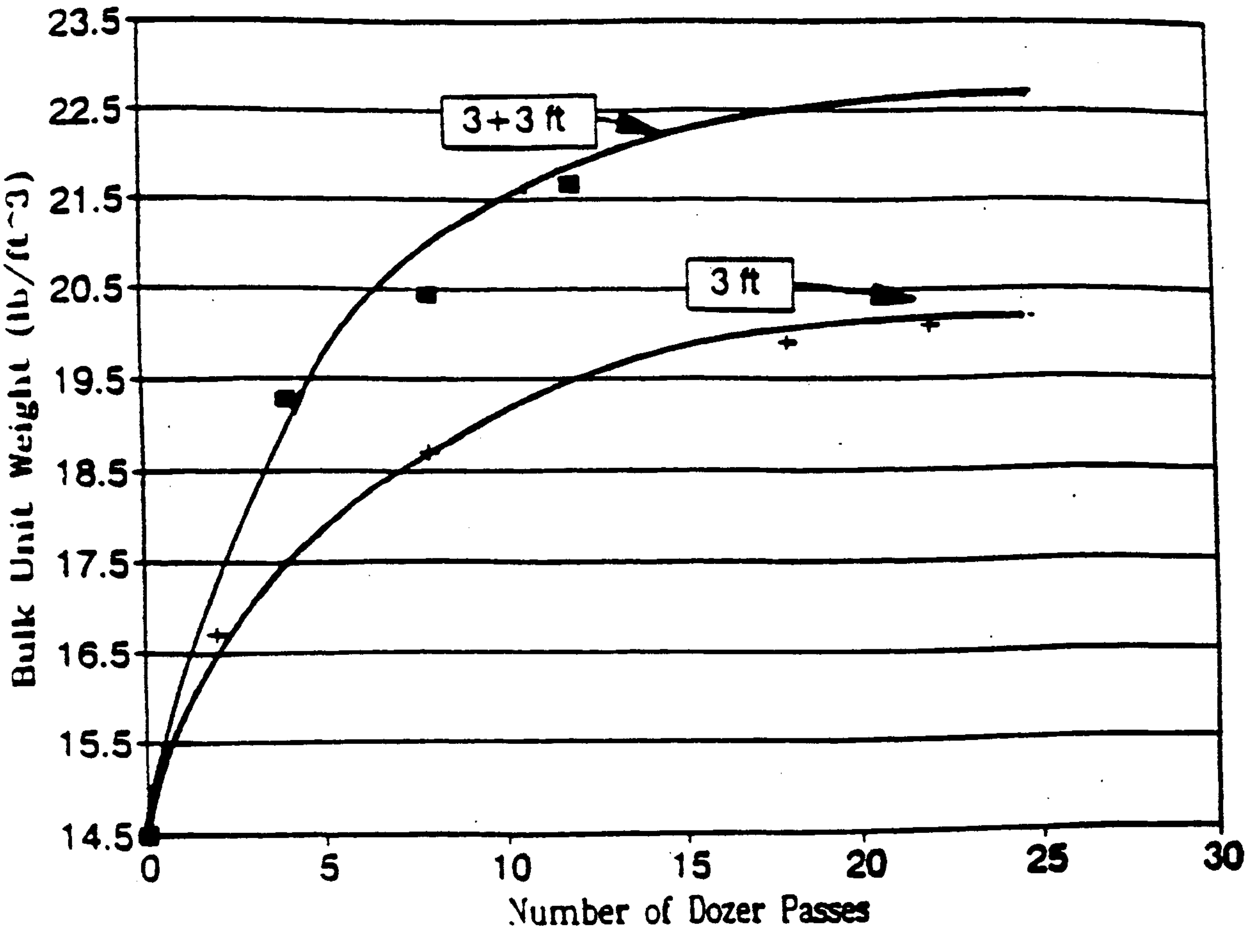


Fig. 45. Bulk unit weight versus compaction effort.

where n is the porosity, G_s is the specific gravity, and γ_w is the unit weight of water. Solving for n

$$n = \frac{G_s \gamma_w - \gamma_t}{G_s \gamma_w} \tag{5}$$

The porosity was calculated taking an average of γ_{tmax} and γ_{tmin}. It was found that the porosity is about 60% for the 2 in. square and 55% for the 2 in. shredded tires.

The porosity of shredded tires used in G. Gotfredson's project was about 79%.

STRENGTH PARAMETERS

Internal Friction Angle and Cohesion

CalTrans conducted triaxial compression tests on 6-in. diameter specimens of the two types of small size shredded tires mentioned before [11]. The obtained cohesion and the internal angle of friction was about 600 lb/ft^2 and 18°, respectively, for the two types of shredded tires; however, no details were presented on the shear failure of the specimen.

Angle of Repose

The angle of repose of the available stockpiles in Minnesota, namely, Mora and Savage, was determined using a transit. The stockpiles are characterized by different average particle area of shredded tires. A summary of the angle repose measurement as well as the average particle area of shredded tires are presented in Table 5. Figure 46 shows the relationship between the angle of repose and the height of the stockpiles. For a design purposes, 45° is a reasonable estimate for the angle of repose.

Table 5. Angle of Repose Measured From Stockpiles.

Pile No.	Location	Height (inches)	Part. Area ($in.^2$)	Angle of Repose (degrees)
1	Mora	96	144	45
2	//	84	//	40
3	//	72	//	40
4	//	48	//	40
5	//	36	//	30
6	//	96	//	50
7	//	72	//	40
8	//	72	//	45
9	//	60	//	45
10	Savage	120	4	50
11	//	144	1	60
12	//	24	4	30
13	//	108	9	45

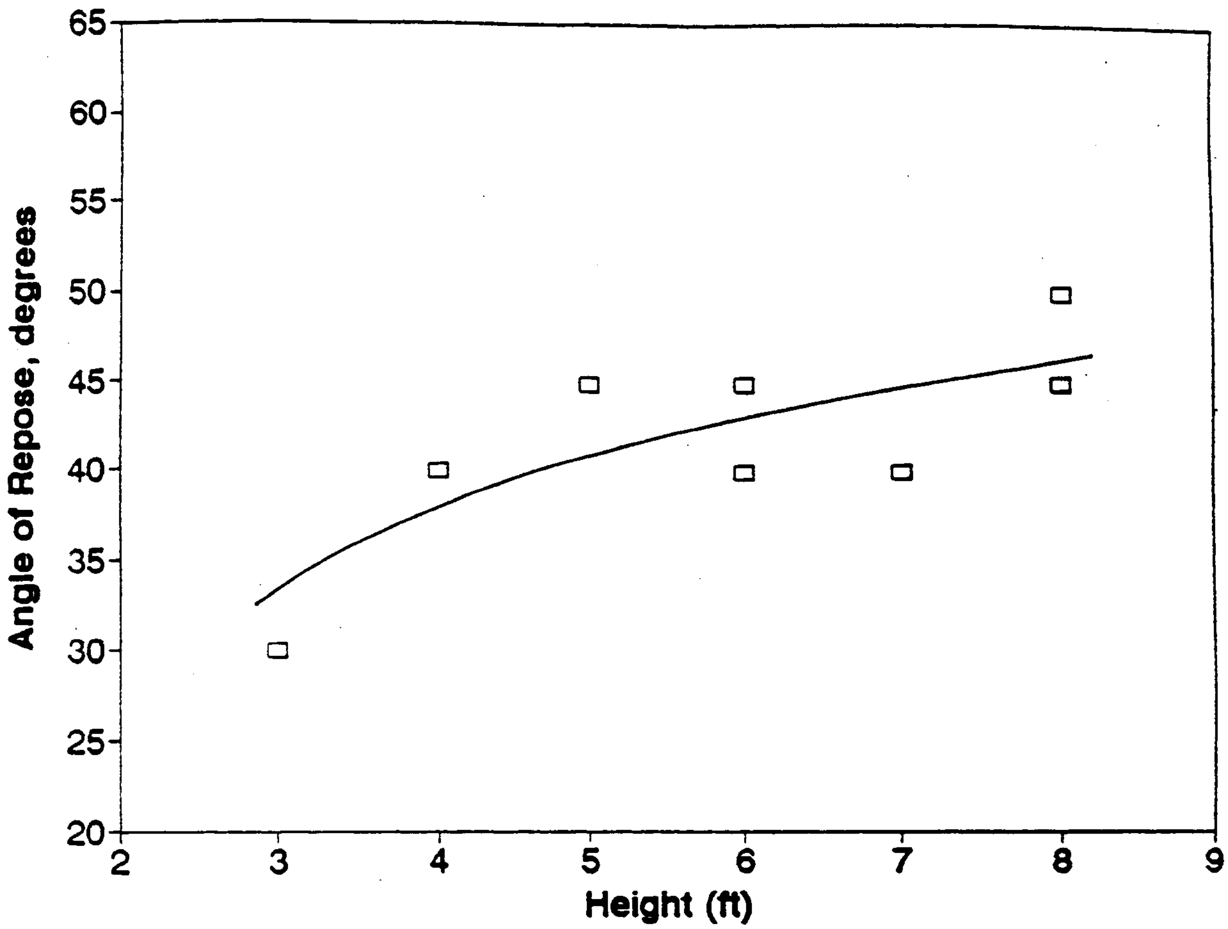


Fig. 46. Angle of repose versus stockpile height.

LABORATORY TESTS FOR COMPRESSIBILITY PARAMETERS

Test Program and Experimentation

One-dimensional compressibility tests were conducted to determine the compressibility parameters of small size (< 2 in.) uncompacted shredded tires and woodchips, namely, compressibility index (C_c) and swelling index (C_s), and to obtain elastic parameters, namely, Young's modulus (E) and Poisson's ratio (ν).

Due to the explatory nature of the proposed laboratory tests, a simple experimental method has been selected, namely, one dimensional compressibility test on large cylindrical samples to accomodate the 2 in. maximum size of the shredded tires and woodchips. The experimental set-up is illustrated in Fig.47. An initial series of tests were performed on samples of shredded tires placed in a cylindrical steel container of 29.3 in. in diameter and 36.9 in. in height and 0.4 in. in thickness. These tests showed a maximum vertical strain of nearly 50% at vertical load of 50 kips. With strains of this magnitude and because of the angular shape of the shredded tires with protruding pieces of steel belt it was felt that there would be a large amount of side friction between the shredded tires and the inside of the cylindrical steel container. To reduce side friction, the inside of the container was lubricated with Micro-Plate 777 grease. In addition, the height of the sample was reduced from 36.9 in. to 25.7 in. To determine Young's modulus and Poisson's ratio for use in subsequent analyses of pavement deflections, the horizontal stresses at the mid-height of the sample were evaluated from measured hoop (circumferential) strains. Hoop strains were measured using four resistance strain gages mounted horizontally 1 ft above the base of the steel container. The correlation used to determine horizontal stress from the measured circumferential strain is

$$\sigma_r = \frac{t}{r} \epsilon_\theta E \tag{6}$$

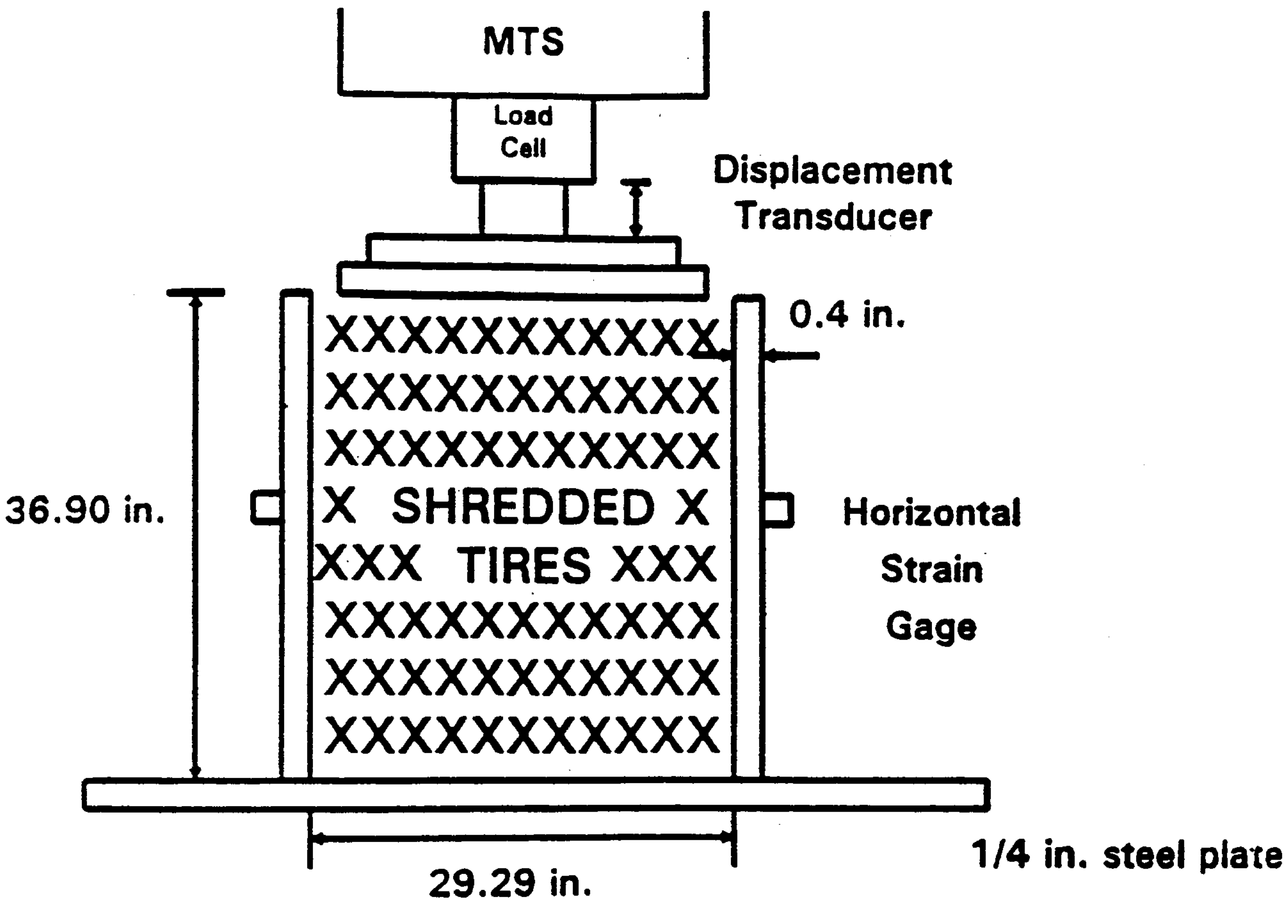


Fig. 47. Compressibility test configuration.

where σ_r is the radial stress, t is the thickness of the cylindrical steel container, r is the radius of the container, ϵ_θ is the average of the four circumferential strains, and E is the Young's modulus of steel, 29,000,000 psi.

The vertical load was applied through a rigid circular 0.25 in.-thick steel plate of 26.7 in. in diameter, welded to another 0.25 in.-thick steel plate of 28.4 in. in diameter. The composite plate rested on the top of the sample and the vertical load was applied with an MTS model 311.415 compression load frame with a capacity of 600 kips. The cylindrical container rested on a steel plate. Some tests involved repetitive loading/unloading cycles. The load was applied using a constant rate of displacement of 0.2 in./min. The measurements of vertical load were performed using either a 25-kip or 600-kip load cell. The vertical stress was calculated as the ratio of the load applied and the cross-section area of the top steel plate

$$\sigma_v = \frac{P}{A} \tag{7}$$

where σ_v is the vertical stress, P is the vertical load applied, and A is the cross-section area of the top steel plate.

The data acquisition of the MTS loading frame provided the readings of the deflection. The vertical strains were calculated as the ratio of the displacement and the initial height of the sample

$$\epsilon_v = \frac{\Delta H}{H_o} \tag{8}$$

where ϵ_v is the vertical strain, ΔH is the displacement, and H_o is the initial height of the sample.

A strain indicator was used to record the circumferential strain at the four strain gages.

Materials

The shredded tires that were used for this study were produced by Maust Tire Recyclers, Inc, Savage, Minnesota, from a mixture of passenger and truck tires. The shredding operation produces a small size shredded tires with the larger pieces of steel belt removed by a magnet. The woodchips that were tested in the laboratory were made from cedar.

The results of gradation tests on three samples of shredded tires and one sample of woodchips fall within a narrow range as shown in Figs.48 and 49, respectively. It is seen that only 10% of the sample of shredded tires is smaller than 1/2 in. size and 50% of the sample falls between the 1 and 1-1/2 in. Figure 49 shows that 65% of the wood chip sample falls between 1 and 1-1/2 in.

The uncompacted bulk unit weight of the three samples of shredded tires and the sample of woodchips was about 30 lb/ft^3, and 9.84 lb/ft^3, respectively. The porosity of an uncompacted sample was calculated from

$$n = \frac{V_v}{V_t} \qquad (9)$$

where n is the porosity, V_v is the volume of voids, and $V_t = V_v + V_s$, V_s is the volume of solids (shredded tires).

The void ratio e_o of the uncompacted samples was calculated from

$$e_o = \frac{V_v}{V_s} = \frac{n}{1 - n} \qquad (10)$$

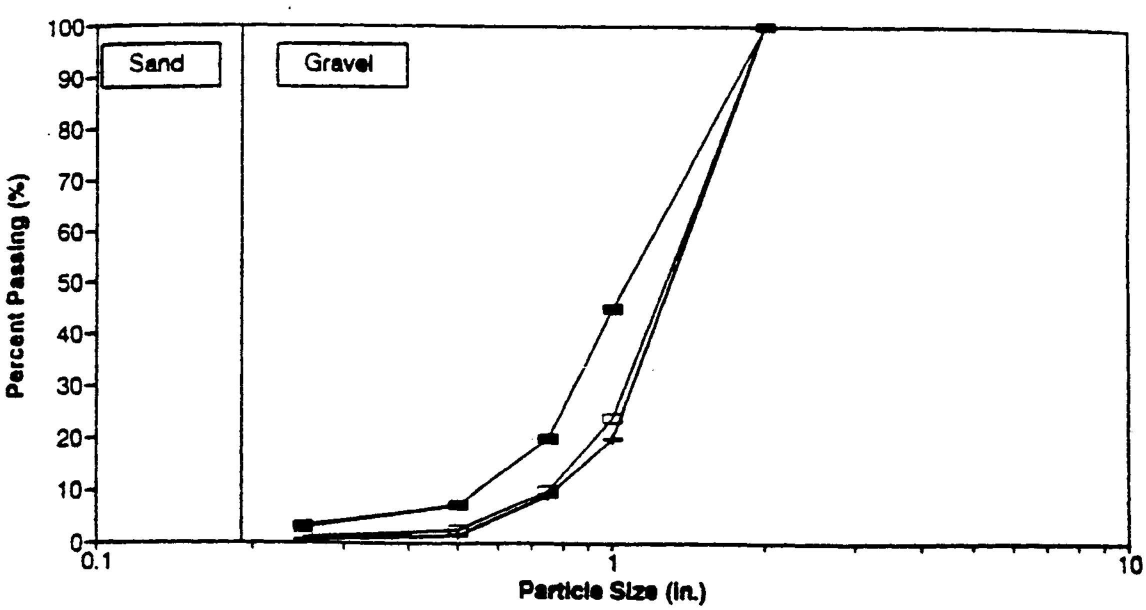


Fig. 48. Particle size distribution curve for shredded tires.

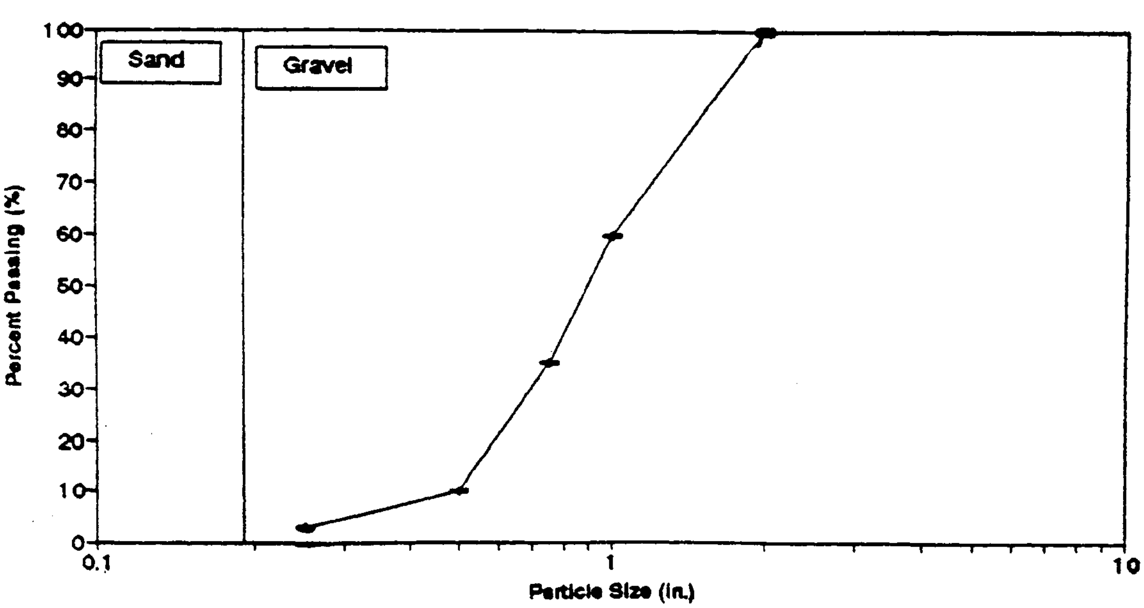


Fig. 49. Particle size distribution curve for woodchips.

To calculate the porosity of the shredded tires and wood chips from equation (9), the volume of voids, V_v, and the total volume, V_t, must be known. A laboratory test was designed to evaluate these volumes.

The shredded tires or woodchips were placed in a 23.4 in. x 23.4 in. x 20 in. plexiglas container to a height of 15 in. covered with a 1/2 in.-thick wooden plate with cross-section slightly less than that of the container. Next, using a pump that was connected to a valve situated on the bottom of the plexiglas container, water was added to shredded tires or woodchips to fill the voids. To make sure that the wooden plate stayed stationary on the top of shredded tires or woodchips when water was added up to bottom of the plate, the plate was clamped between angles which were affixed to the side of the container with double face foam tape. After the shredded tires or woodchips were filled with water, the water was drained and measured using a cylindrical container graduated in ml. The average volume of water that filled the shredded tires and woodchips was about 79,000 ml, and 92,996 ml, respectively. This volume was assumed to be equal to the volume of voids (V_v); the total volume (V_t) was about 138,800 ml. The estimated value of porosity evaluated by CalTrans on shredded tires (<2 in.) was about 55-60% which is approximately equal to the porosity of shredded tires tested in the laboratory.

From equation (10) the initial void ratio (e_0) for shredded tires and woodchips was found to be about 1.33, and 2.00, respectively.

The specific gravity of shredded tires was calculated from

$$\gamma_t = \frac{G_s}{1 + e_0}\gamma_w \tag{11}$$

which can be rewritten as

$$G_s = \frac{\gamma_t}{\gamma_w}(1 + e_o) \tag{12}$$

where G_s is the specific gravity, γ_t is the bulk unit weight, and γ_w is the unit weight of water.

The specific gravity for shredded tires and woodchips was found to be 1.08, and 0.46, respectively. Thus the specific gravity for shredded tires is slightly greater than that of water.

Test Results

Compressibility results on three samples of uncompacted shredded tires and one sample of woodchips are shown in Figs.50 and 51, respectively. It is seen that for shredded tires a vertical stress of only 8 psi causes 20 to 25% vertical strain. Increasing the stress from 8 psi to 55 psi causes an additional 15% to 20% vertical strain. Therefore, at low levels of vertical stress, the deflection of shredded tires is high; however, the deflection decreases significantly as the vertical stress level increases.

Figure 51 depicts that a vertical stress of about 200 psi causes 20-25% of vertical strain in the wood chips. Increasing the stress from 200 to 600 psi causes an additional 4% vertical strain.

The effect of multiple cycles of loading and unloading shredded tires was investigated by cycling the vertical stress between a maximum of 68 psi and a minimum of about 5.3 psi. The lower limit is equivalent to an overburden of 6 ft of gravel. Cycling between the upper and lower limit caused 10 to 40% elastic strain in the three trials that were conducted. A typical test result is shown in Fig.52.

Figure 53 illustrates that cycling on woodchips with a vertical stress between a maximun of 600 and a minimum of about 5.3 psi caused 2 to 5% elastic strain.

Horizontal (radial) stresses were measured during the compression tests and are shown vs. vertical stress for the three samples of shredded tires and the

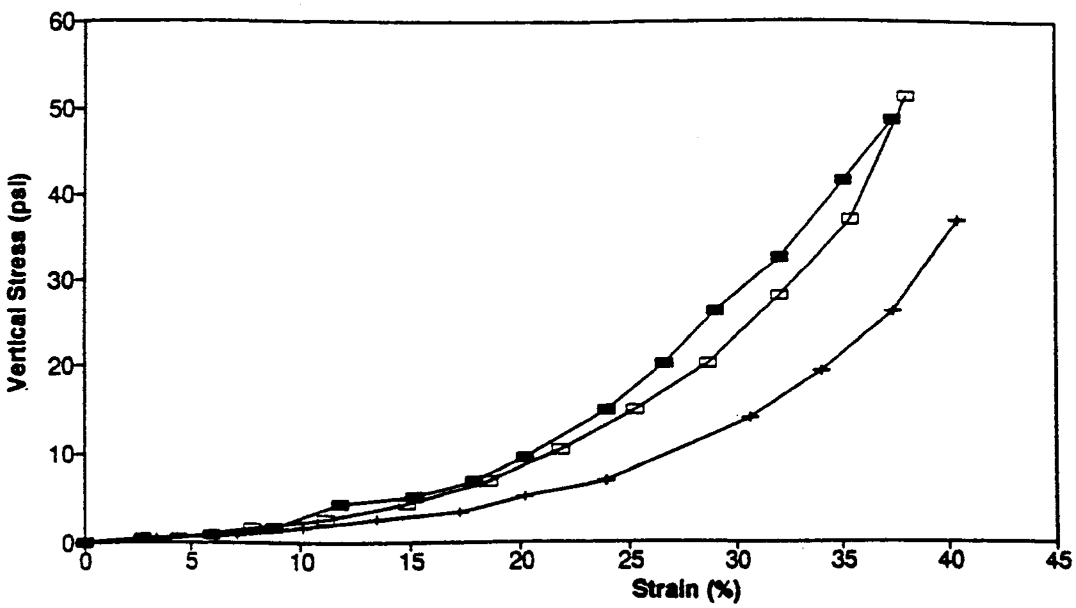


Fig. 50. Vertical stress versus vertical strain for shredded tires.

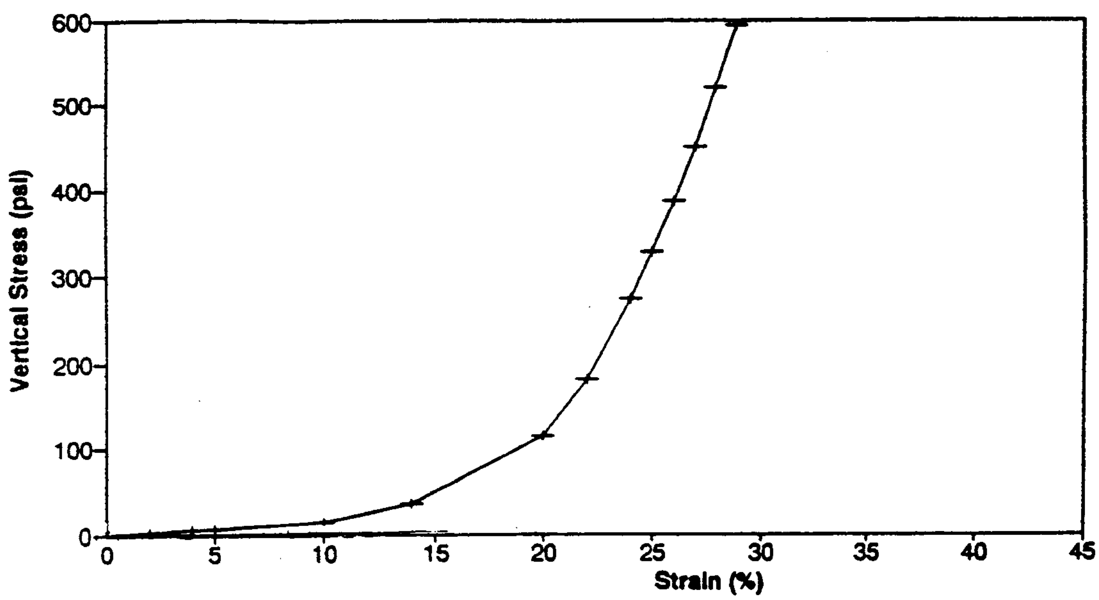


Fig. 51. Vertical stress versus vertical strain for woodchips.

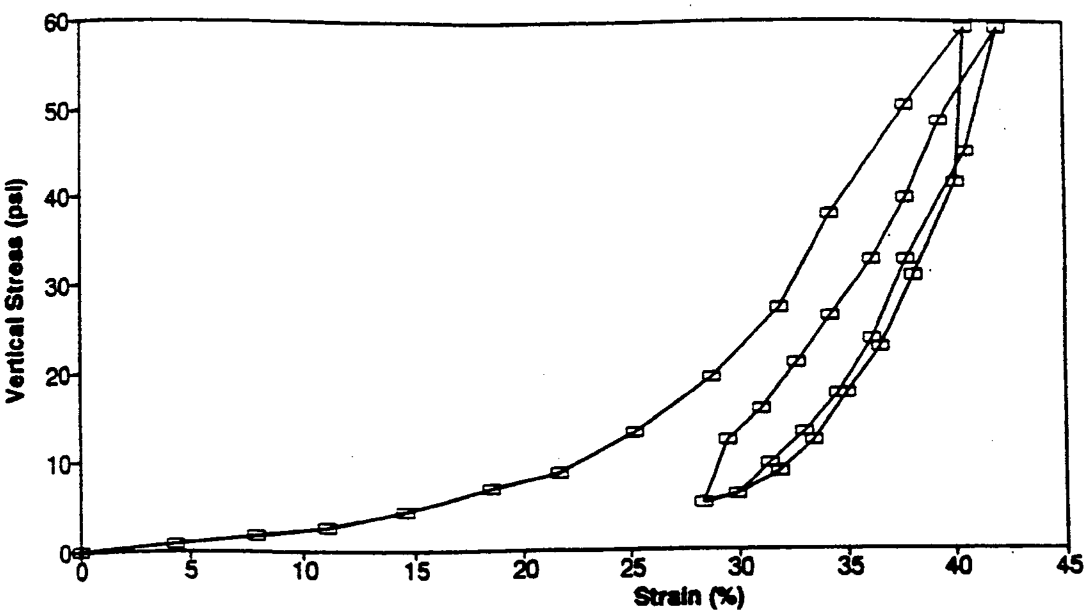


Fig. 52. Vertical stress versus vertical strain for multiple cycles on shredded tires.

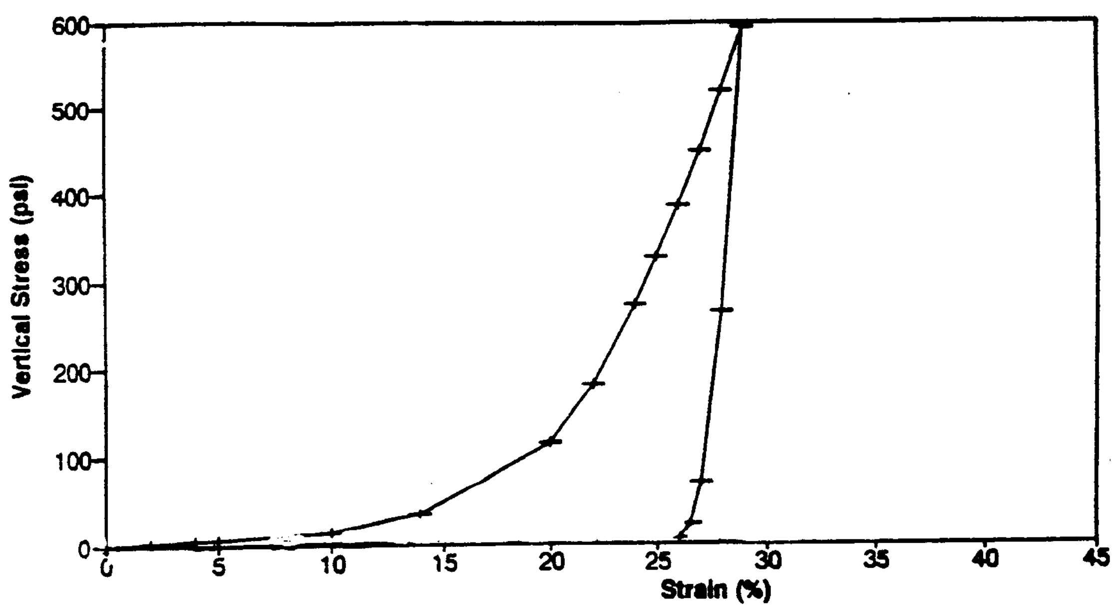


Fig. 53. Vertical stress versus vertical strain for one cycle on woodchips.

sample of woodchips in Fig.54 and 55, respectively. The vertical stress at the level of horizontal strain gages was assumed to be equal to the vertical stress at the top of the plate because it was assumed that there is no load carried out by the container.

All tests on shredded tires exhibited a bilinear relationship between the horizontal and vertical stress with the slope increasing at a vertical stress of about 25 psi. The coefficients of lateral pressure (K) are the slopes of the straight lines. The average value was about 0.4 before the change in slope and about 0.96 after the change in the slope for the three tests in Fig.54.

Figure 55 shows that the coefficient of lateral pressure (K) of cedar woodchips was about 0.36.

Figure 56 shows the relationship between the void ratio and decimal logarithm of the vertical stress for the first loading and unloading cycle for shredded tires. The compressibility index and the swelling index are the slopes of the two lines corresponding to the initial loading part and to the unloading part, respectively in Fig.56. The compressibility and the swelling indexes of shredded tires were found to be C_c=0.50, and C_s=0.27, respectively. The second loading and unloading cycle gives a swelling index C_s=0.27 which is equal to that of the first cycle.

A similar relationship was established for woodchips as shown in Fig.57; the compressibilty and swelling indices of woodchips were found to be 0.35 and 0.03, respectively.

The comparison of Figs.52 and 53 shows that the loading portion of the curve for wood chips is much steeper than that for shredded tires. A similar observation can be made for the unloading portion of the curve. The latter means that cedar wood chips is stiffer material than shredded tires.

The values of the compressibility and swelling indices of shredded tires and wood chips are summarized in Table 6.

For typical natural soils, the value of the swelling index (C_s) is, in most cases, 1/4 to 1/5 of the compression index (C_c). Table 6 shows C_s for shredded tires and wood chips are about 1/2, and 1/10 of C_c, respectively.

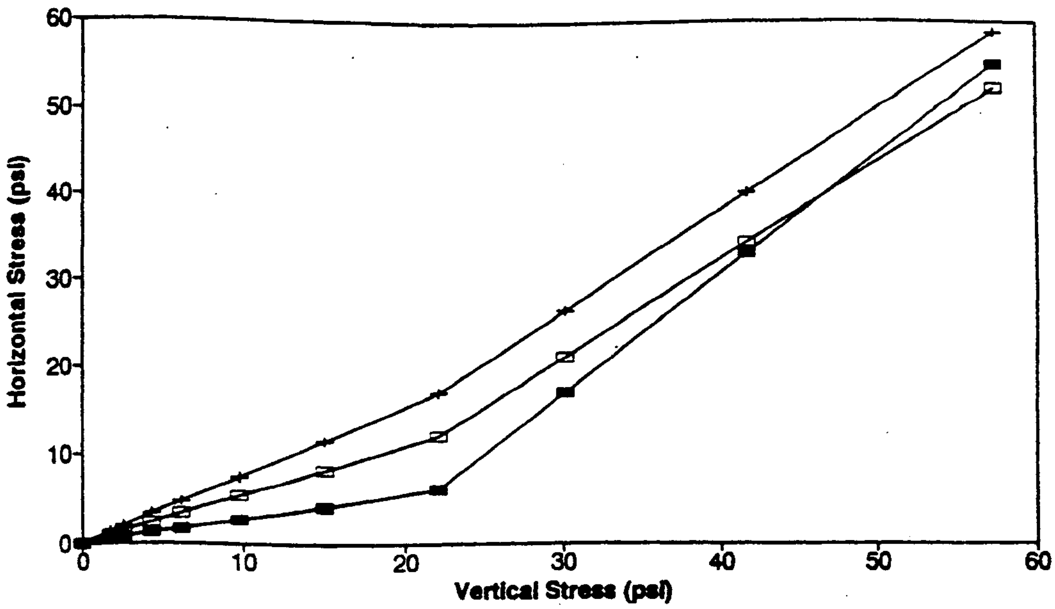


Fig. 54. Horizontal stress versus vertical stress for shredded tires.

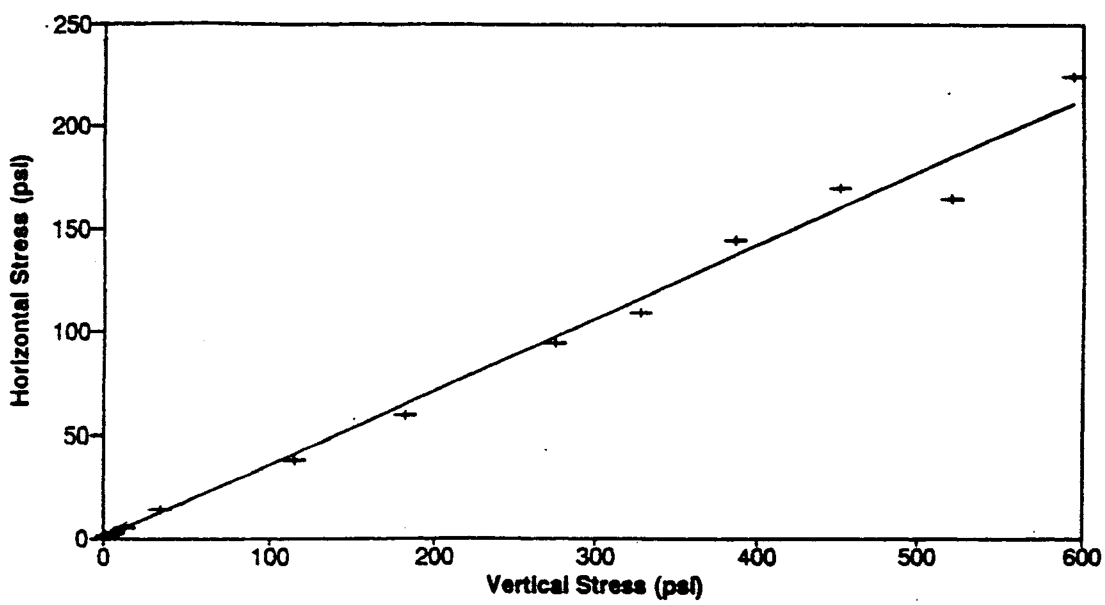


Fig. 55. Horizontal stress versus vertical stress for woodchips.

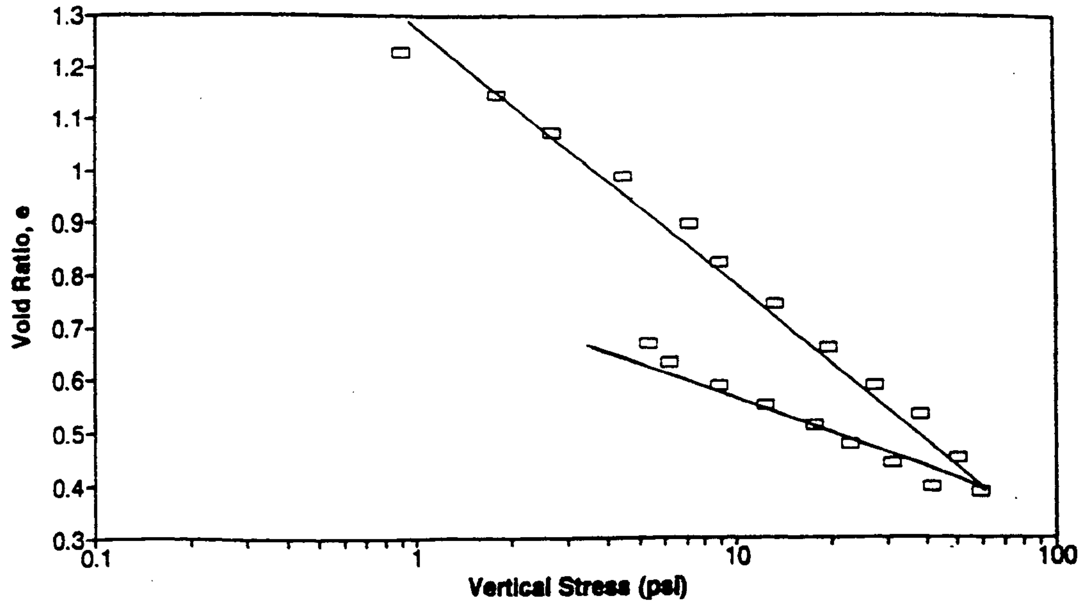


Fig. 56. Compressibility curve for shredded tires.

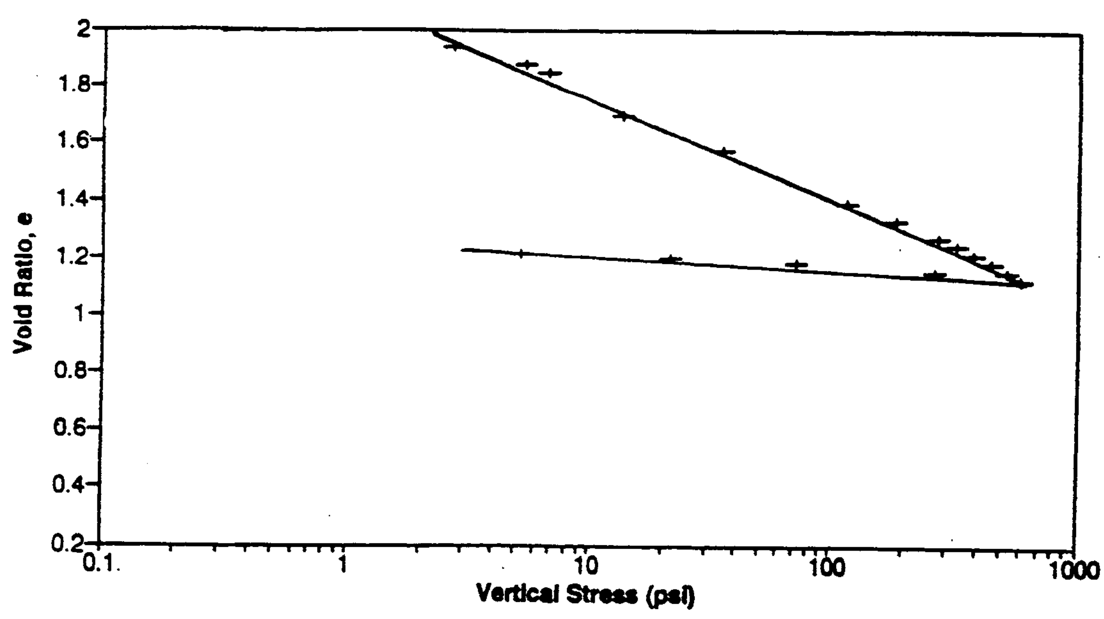


Fig. 57. Compressibility curve for woodchips.

The analysis of data in the light of the elasticity theory for use in the deflection analysis of a pavement system containing shredded tires as a lightweight fill is presented in the next chapter.

Table 6. Compressibility and Swelling Indices For Shredded Tires and Woodchips.

Material	Test no.	C_c	C_s
Shredded Tires	1	0.49	0.26
	2	0.51	0.27
	3	0.52	0.28
	Average	0.5	0.27
Wood chips	1	0.35	0.03

CHAPTER 7

PAVEMENT DEFLECTION ANALYSIS USING SHREDDED TIRES AS A LIGHTWEIGHT FILL

This section presents a deflection analysis of an asphalt concrete pavement using a shredded tire lightweight fill comprising pieces of < 2 in. size. The analysis makes use of the multilayer linear elstic program ELSYM5 developed at the University of New Hampshire in 1984. The Young's modulus and Poisson's ratio of the shredded tire fill were determined from one-dimensional compression tests described in Chapter 6. In determining appropriate values of Young's modulus and Poisson's ratio, an account was taken of possible anisotropy of the shredded tire layer. Graphs are presented which relate the deflection of the pavement surface at the center point of an equivalent wheel load to the thickness of the granular base and asphalt concrete layer for a given thickness of the shredded tire fill. These can be used as design guidelines for selecting the appropriate thickness for the shredded tire fill.

MULTILAYER ELASTIC ANALYSIS

Computer program ELSYM5 permits for evaluating deflections of a pavement system consisting of several different layers subjected to a uniformly distributed load acting over a circular area. Each layer is assumed to be linearly elastic and isotropic. In the analysis presented herein, a system comprising four layers was considered (Fig.58): 1) asphalt concrete layer, 2) granular base, 3) shredded tire fill, 4) rigid subgrade.

A single load of 9000 lbs, and tire pressure of 80 psi, were assumed in the analysis which corresponds to the radius of the loaded area of 5.96 in. The deflections of the mulilayer system were determined at only one point located at the center of the loaded area on the pavement's surface. The Young's moduli and Poisson's ratios for layers 1), 2), and 4) were selected as:

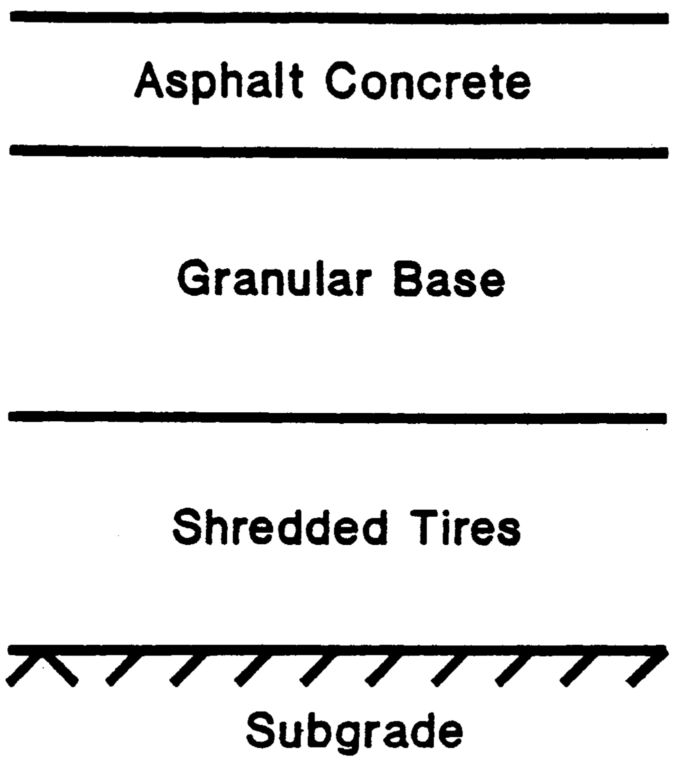


Fig. 58. Four-layer pavement system.

1) asphalt concrete: E=500 ksi, v=0.35

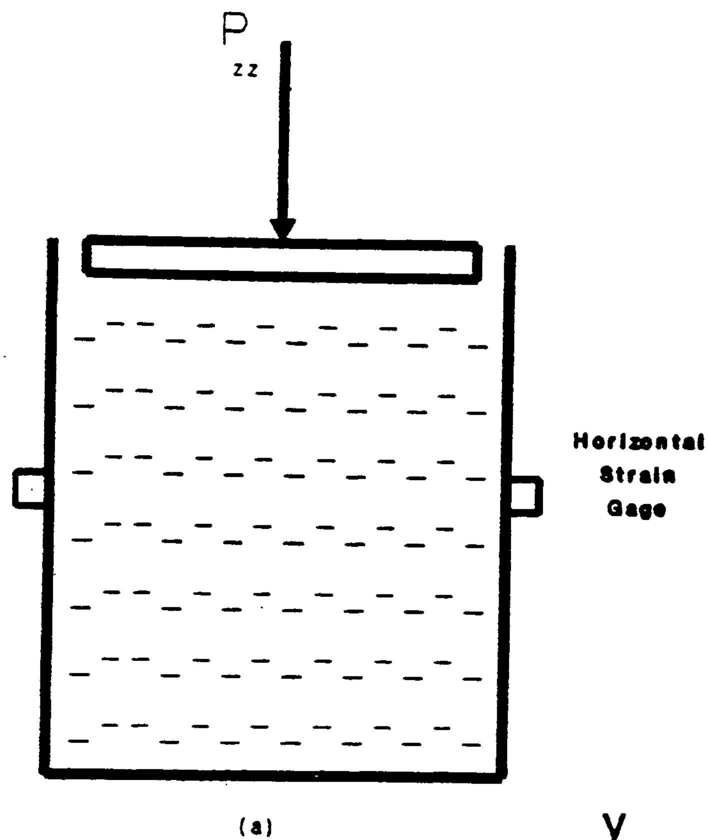
2) granular base: E=20 ksi, v=0.25

4) rigid subgrade: E=1000 ksi, v=0.25

The Young's modulus and Poisson's ratio of the shredded tire fill - layer 3) - were determined from one-dimensional compression tests using the equations of linear elasticity for isotropic or anisotropic material.

TEST RESULTS OF ONE-DIMENSIONAL COMPRESSION

In a one-dimensional compression test in a stiff confining cylinder (Fig.59a), instrumented with strain gages measuring the hoop (circumferential) strains in cylinder's wall, the following quantities can be measured or calculated: 1) axial stress σ_{zz}, 2) axial strain ϵ_{zz}, and 3) horizontal stress $\sigma_{xx}=\sigma_{yy}$ (Fig.59b). Appendix B presents the average values of these quantities obtained from 3 tests (see Chapter 6). Figures 60 and 61 show the relationship between the vertical stress and vertical strain, and the horizontal stress and vertical stress, respectively, for loading and unloading/reloading cycles. Clearly, for both the loading part and the unloading/reloading part these relationships are non-linear, with much greater non-linearity for the loading part. This implies that the shredded tires do not behave as a linear elastic material. As in pavement construction the shredded tires are always compacted, the unloading/reloading part of the one-dimensional compression test is more representative for evaluating the deflections. Therefore, the loading part of the tests was disregarded, and the unloading/reloading part was approximated by a linear relationship (broken lines in Figs.60 and 61); a similar approximation was applied to the horizontal stress and vertical stress. These approximations lead to the following relationship between the axial stress and axial strain, and the horizontal stress and vertical stress



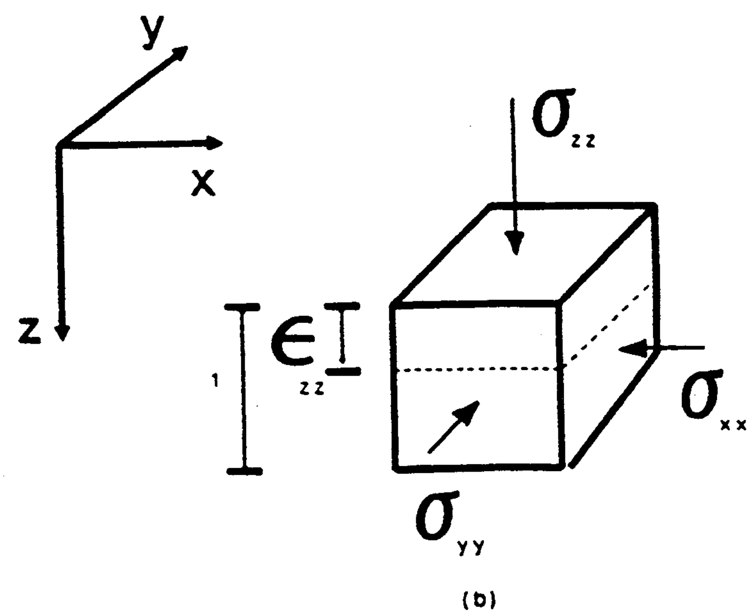


Fig. 59. a) One-dimensional compression test, b) Stesses and strains determined in test.

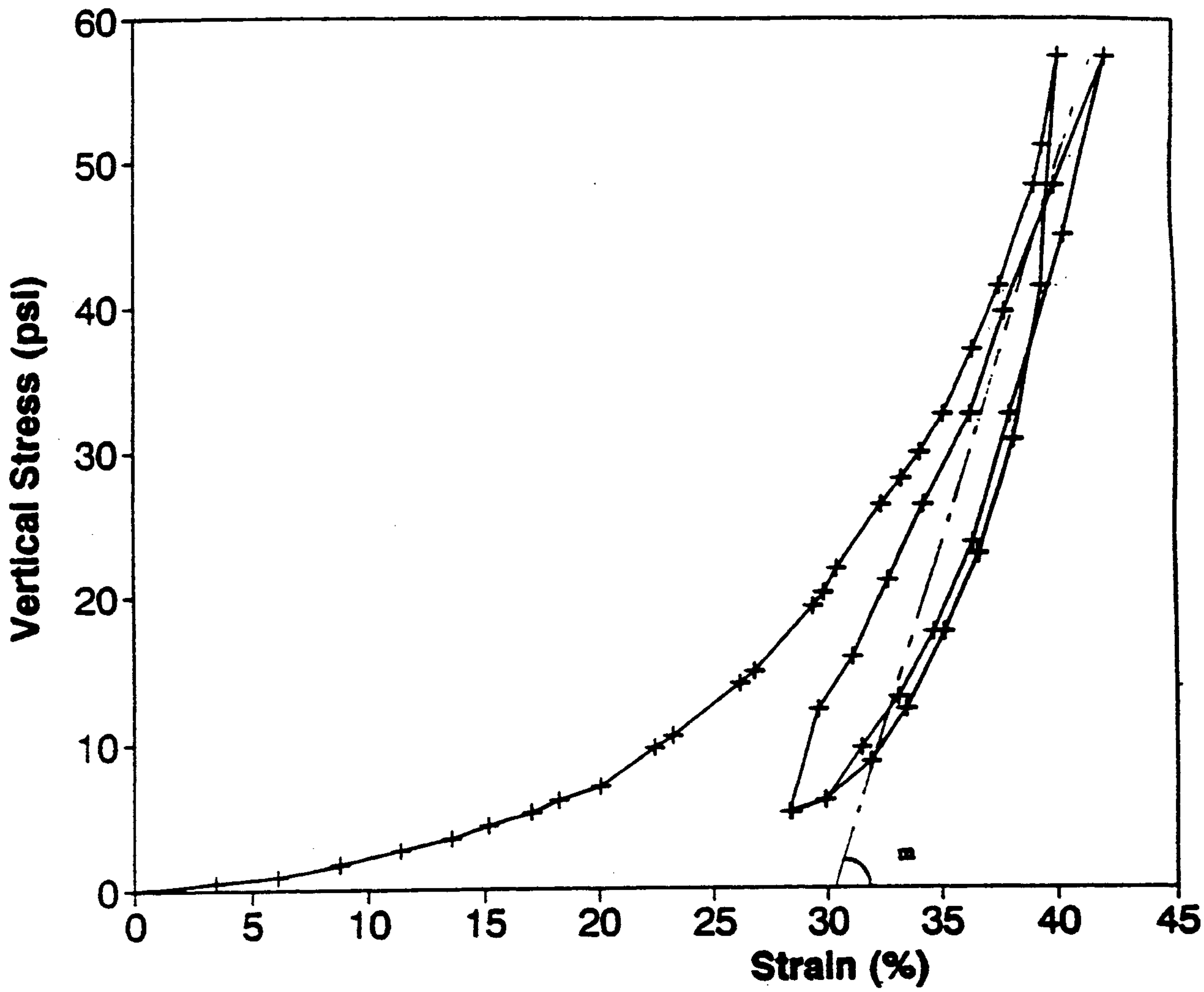


Fig. 60. Vertical stress as a function of vertical strain.

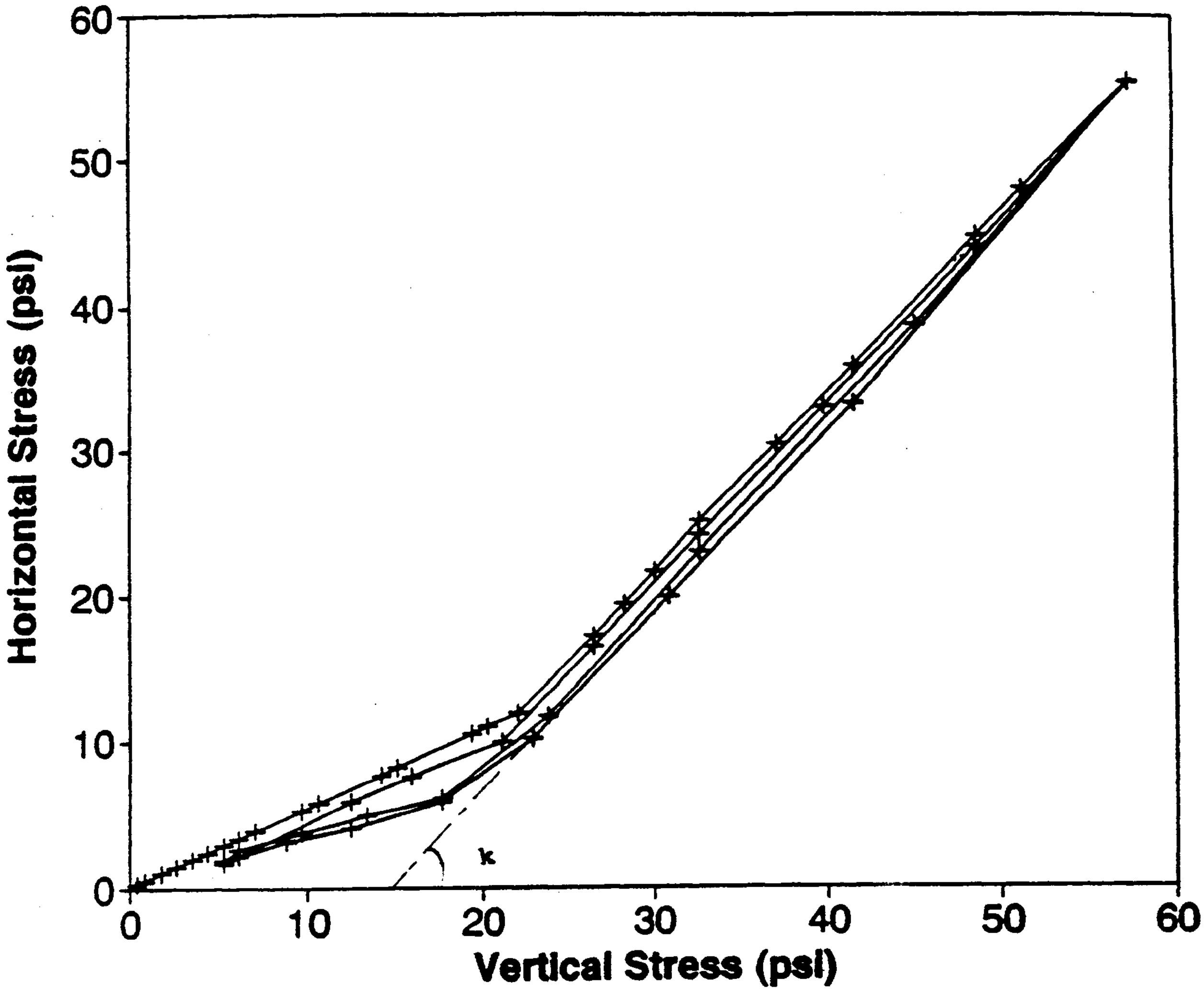


Fig. 61. Horizontal stress as a function of vertical stress.

$$\sigma_{zz} = m\ \epsilon_{zz} \qquad (13)$$

$$\sigma_{xx} = \sigma_{yy} = K\ \sigma_{zz} \qquad (14)$$

where

$m = 430$ psi (15)

$K = 0.82$ (16)

Relationships (13) and (14) were subsequently used to determine Young's modulus and Poisson's ratio of the shredded tire fill for the use in the multilayer deflection analysis. This was done by assuming that the shredded tires are an isotropic or an anisotropic-transversly isotropic linear elastic material.

SHREDDED TIRES AS AN ISOTROPIC MATERIAL

If the shredded tire fill is regarded as an isotropic linear elastic material. i.e., its properties are the same in all directions, the relationships between the stresses and strains are given by the following generalized Hooke's law

$$\epsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - \nu\left(\sigma_{yy} + \sigma_{zz}\right)\right]$$

$$\epsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - \nu\left(\sigma_{xx} + \sigma_{zz}\right)\right] \qquad (17)$$

$$\epsilon_{zz} = \frac{1}{E}\left[\sigma_{ZZ} - \nu\left(\sigma_{xx} + \sigma_{yy}\right)\right]$$

$$\epsilon_{xy} = \frac{1}{2G}\sigma_{xy}$$

$$\epsilon_{xz} = \frac{1}{2G}\sigma_{xz} \quad (18)$$

$$\epsilon_{yz} = \frac{1}{2G}\sigma_{yz}$$

where E is the Young's modulus, ν is the Poisson's ratio, and

$$G = \frac{E}{2(1+\nu)} \quad (19)$$

The values of E and ν can be determined from equations (17), relations (13) and (14), and conditions that in the one-dimensional compression test

$$\epsilon_{xx} = \epsilon_{yy} = 0 \quad (20)$$

$$\sigma_{xx} = \sigma_{yy} \quad (21)$$

From conditions (20) and (21), relation (14), and from the first of equations (17), we have

$$\nu = \frac{K}{1+K} \quad (22)$$

From the third of equations (17), condition (21), and relations (13) and (14)

$$E = (1 - 2\nu K)m \quad (23)$$

On substituting m and K from (15) and (16) into equations (22) and (23), we arrive finally at

$$E = 112.66 \text{ psi} \tag{24}$$

$$\nu = 0.45 \tag{25}$$

SHREDDED TIRES AS AN ANISOTROPIC-TRANSVERSLY ISOTROPIC MATERIAL

The internal structure of a shredded tire layer (Fig.62a) can be represented by a honeycomb structure with elongated cells in the horizontal direction (Fig.62b). This structure forms during gravitational deposition of flaky-shape pieces and subsequent compaction. The elongation of the cells implies that the response to external load is different in the vertical and horizontal directions, and the material no longer can be regarded as isotropic. A material with different response in different directions is termed *anisotropic*; a particular type of anisotropy relevant for the shredded tire fill is termed *transversly isotropic*.

In a transversly isotropic material the response in any direction in the x,y-plane (horizontal) is the same (isotropic), and differs from the response in any other direction. The equations relating the stresses and strains for an elastic transversly isotropic material are

$$\begin{aligned}
\epsilon_{xx} &= \frac{1}{E_x}\sigma_{xx} - \frac{\nu_{yx}}{E_y}\sigma_{yy} - \frac{\nu_{zx}}{E_z}\sigma_{zz} \\
\epsilon_{yy} &= -\frac{\nu_{xy}}{E_x}\sigma_{xx} + \frac{1}{E_y}\sigma_{yy} - \frac{\nu_{zy}}{E_z}\sigma_{zz} \\
\epsilon_{zz} &= -\frac{\nu_{xz}}{E_x}\sigma_{xx} - \frac{\nu_{yz}}{E_y}\sigma_{yy} + \frac{1}{E_z}\sigma_{zz}
\end{aligned} \tag{26}$$

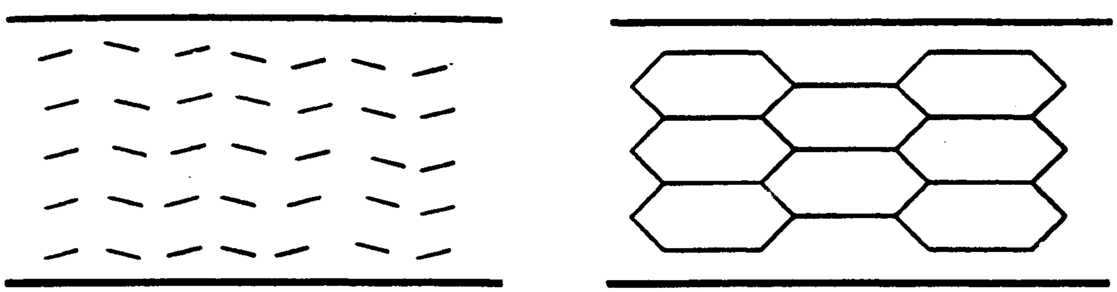


Fig. 62. a) Schematic of internal structure of shredded tires.
b) Honeycomb structure with elongated cells.

$$\epsilon_{xy} = \frac{1}{G_{xy}} \sigma_{xy}$$

$$\epsilon_{xz} = \frac{1}{2G_{xz}} \sigma_{xz} \qquad (27)$$

$$\epsilon_{yz} = \frac{1}{2G_{yz}} \sigma_{yz}$$

with

$$E_x = E_y = E$$

$$E_z = E'$$

$$\nu_{yx} = \nu_{xy} = \nu$$

$$\nu_{zx} = \nu_{zy} = \nu' \qquad (28)$$

$$\nu_{xz} = \nu'' = \nu' \frac{E}{E'}$$

$$G_{xy} = \frac{E}{2(1 + \nu)}$$

$$G_{xz} = G_{yz} = G'$$

Using relations (28), equations (26) and (27) can be written as

$$\epsilon_{xx} = \frac{1}{E} \sigma_{xx} - \frac{\nu}{E} \sigma_{yy} - \frac{\nu'}{E'} \sigma_{zz}$$

$$\epsilon_{yy} = -\frac{\nu}{E}\sigma_{xx} + \frac{1}{E}\sigma_{yy} - \frac{\nu'}{E'}\sigma_{zz}$$

$$\epsilon_{zz} = -\frac{\nu'}{E'}\sigma_{xx} - \frac{\nu'}{E'}\sigma_{yy} + \frac{1}{E'}\sigma_{zz} \qquad (29)$$

$$\epsilon_{xy} = \frac{1 + \nu}{E}\sigma_{xy}$$

$$\epsilon_{xz} = \frac{1}{2G'}\sigma_{xz} \qquad (30)$$

$$\epsilon_{yz} = \frac{1}{2G'}\sigma_{yz}$$

In contrast to equations (17) and (18), equations (29) and (30) contain five independent material constants: two Young's moduli, E and E', two Poisson's ratios, ν and ν', and one shear modulus, G'. These constants cannot be determined from the one-dimensional compression tests in which the material is compressed in the z-direction, and tests are required where the material is compressed in other directions. It is possible, however, to assess the influence of two assumed constants, say ν and ν', on Young's moduli E and E'.

From the third of equations (29), condition (21), relations (13) and (14), and the fifth of relations (28), we obtain

$$E' = m(1 - 2\nu' K) \qquad (31)$$

Likewise, from the first of equations (29), conditions (20) and (21), and relation (14)

$$E = KE'\frac{1 - \nu}{\nu'} \qquad (32)$$

In addition, in view of the fifth of equations (28), Poisson's ratio ν'' is given by

$$\nu'' = K(1 - \nu) \tag{33}$$

Since the compressibility of the honeycomb structure of Fig.62b is greater in the z-direction than in the x- or y-direction, the range for ν and ν', both being positive numbers, should be such that $E'<E$. Also, it is reasonable to assume that ν, ν', and ν'', are less than or equal to 0.5.

Once the Young's moduli and Poisson's ratios are known, they can be averaged to obtain material constants for a *fictitious* isotropic material with only two material constants E_a and ν_a

$$E_a = \frac{1}{3}(2E + E') \tag{34}$$

$$\nu_a = \frac{1}{3}(\nu + \nu' + \nu'') \tag{35}$$

which can be used in the multilayer linear elastic program ELSYM5 to assess, approximately at least, the influence of the shredded tires anisotropy on the asphalt concrete deflections.

Figures 63 and 64 show the dependence of the average Young's modulus E_a and Poisson's ratio ν_a on the Poisson's ratios ν and ν' for which $E'<E$; the values of m and K were taken as measured in the tests (expressions (15) and (16)). For comparison, Young's modulus E and Poisson's ratio ν for an elastic isotropic material (expressions (24) and (25)) are drawn as broken lines. It is seen that for a wide range of small values of ν' the average Young's modulus E_a is greater than E, and the average Poisson's ratio ν_a is less than ν; only for ν close to 0.5 do we have $E_a<E$.

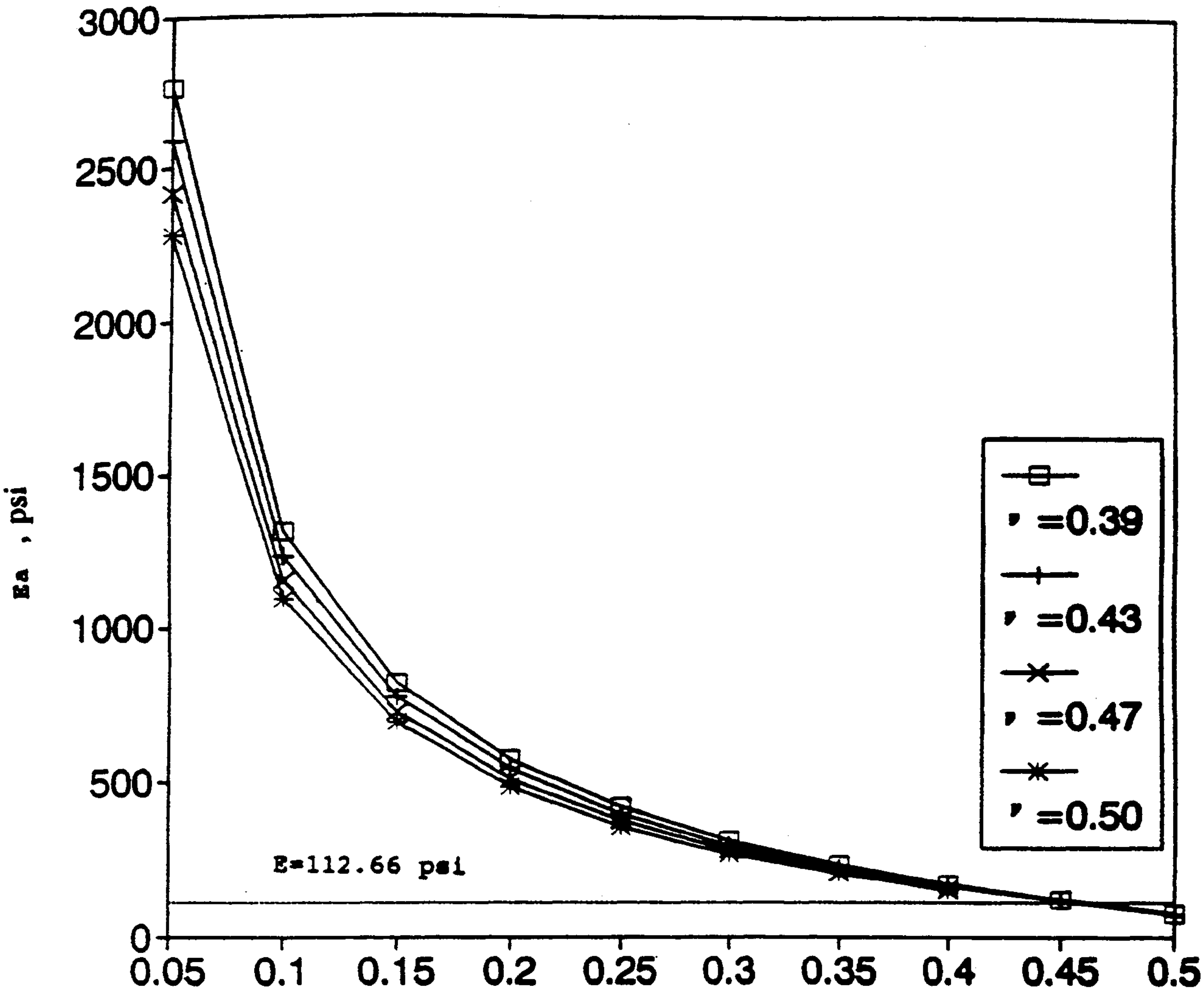


Fig. 63. Average Young's modulus as a function of ν and ν′.

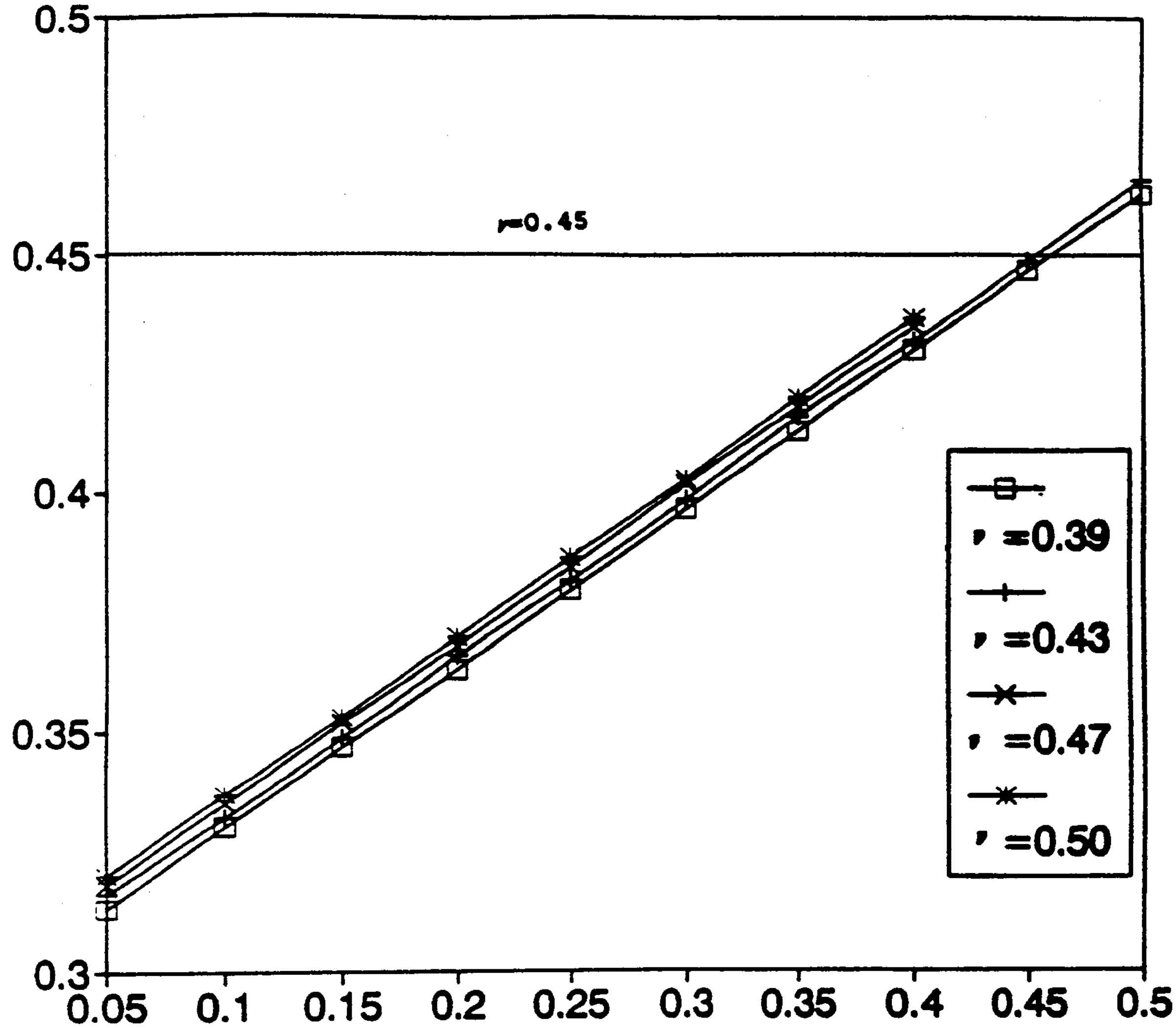


Fig. 64. Average Poisson's ratio as a function of ν and ν'.

DEFLECTIONS

This section presents results of pavement deflection calculations using program ELSYM5 and Young's modulus and Poisson's ratio of the shredded tire fill regarded as: a) a true isotropic elastic material with E and ν (Figs.65 - 67), and b) a fictitious isotropic elastic material with E_a and ν_a approximating the anisotropic-transversly isotropic material (Figs.68 - 73). Each graph is constructed for a given value of the thickness of the shredded tire fill (1 ft, 2 ft, and 3 ft). Two sets of values of the average Young's modulus and Poisson's ratio for the fictitious isotropic material were selected from the graphs shown in Figs.63 and 64: E_a=235.58 psi, ν_a=0.413, and E_a=77.42 psi, ν_a=0.463. Note that in the first set $E_a>E$ and $\nu_a<\nu$, whereas in the second $E_a<E$ and $\nu_a>\nu$.

Figure 74 shows the dependence of deflections on E_a and E. It is evident that for the fictitious isotropic material the deflections increase with the decrease in E_a in spite of the increase in ν_a; it should be remembered, however, that in the case considered, both constants are interrelated through the assumed values of Poisson's ratios $\nu=\nu_{xy}$ and $\nu'=\nu_{zx}$. As the deflection analysis for the anisotropic-transversly isotropic material is approximate (a fictitious isotropic material is considered) it is difficult to assess the influence of material anisotropy. A more conclusive analysis would require other tests and a computer code that incorporates material anisotropy.

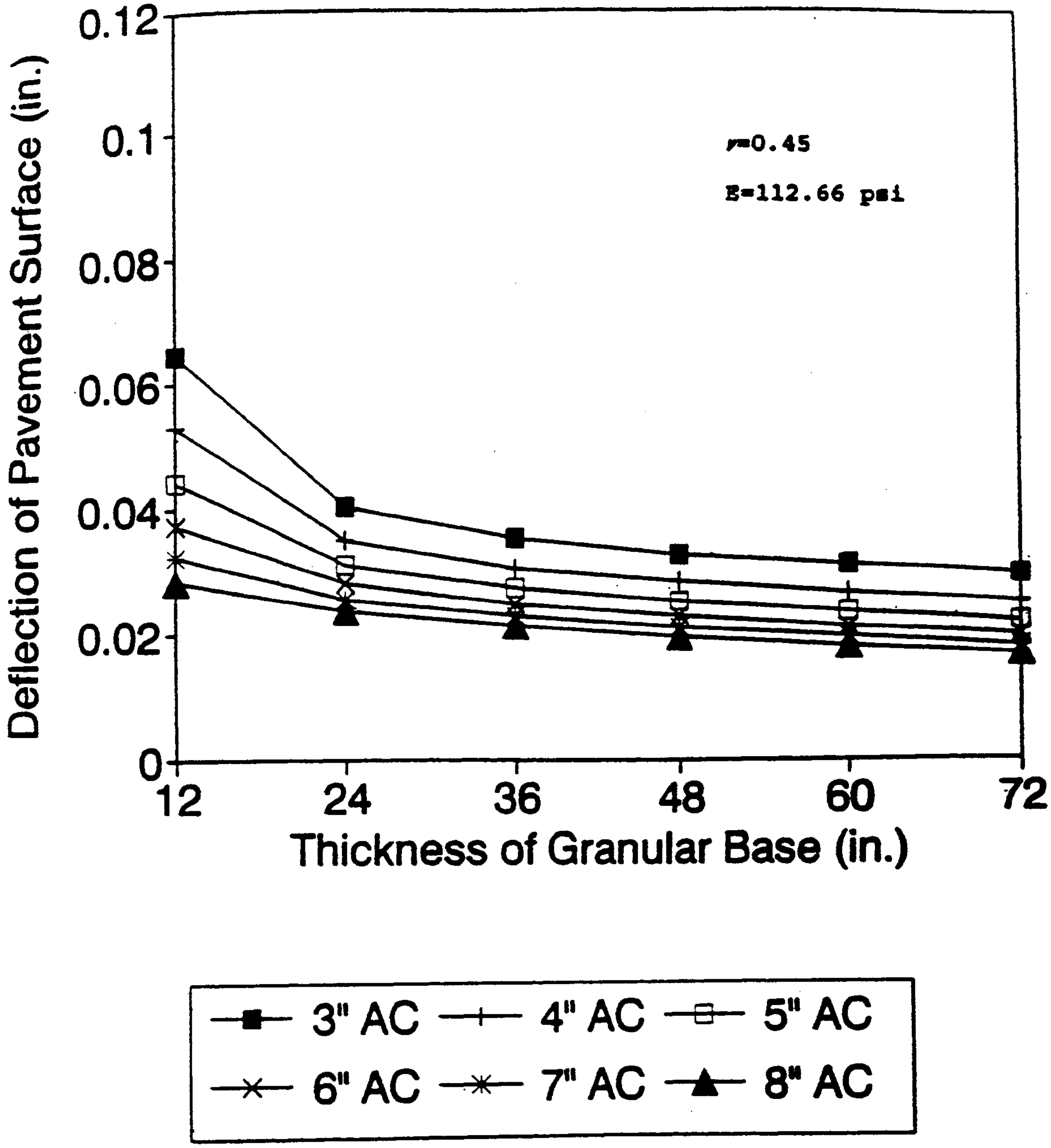


Fig. 65. Surface deflections as a function of asphalt concrete and granular base thickness for a 1-ft shredded tire layer (isotropic, elastic).

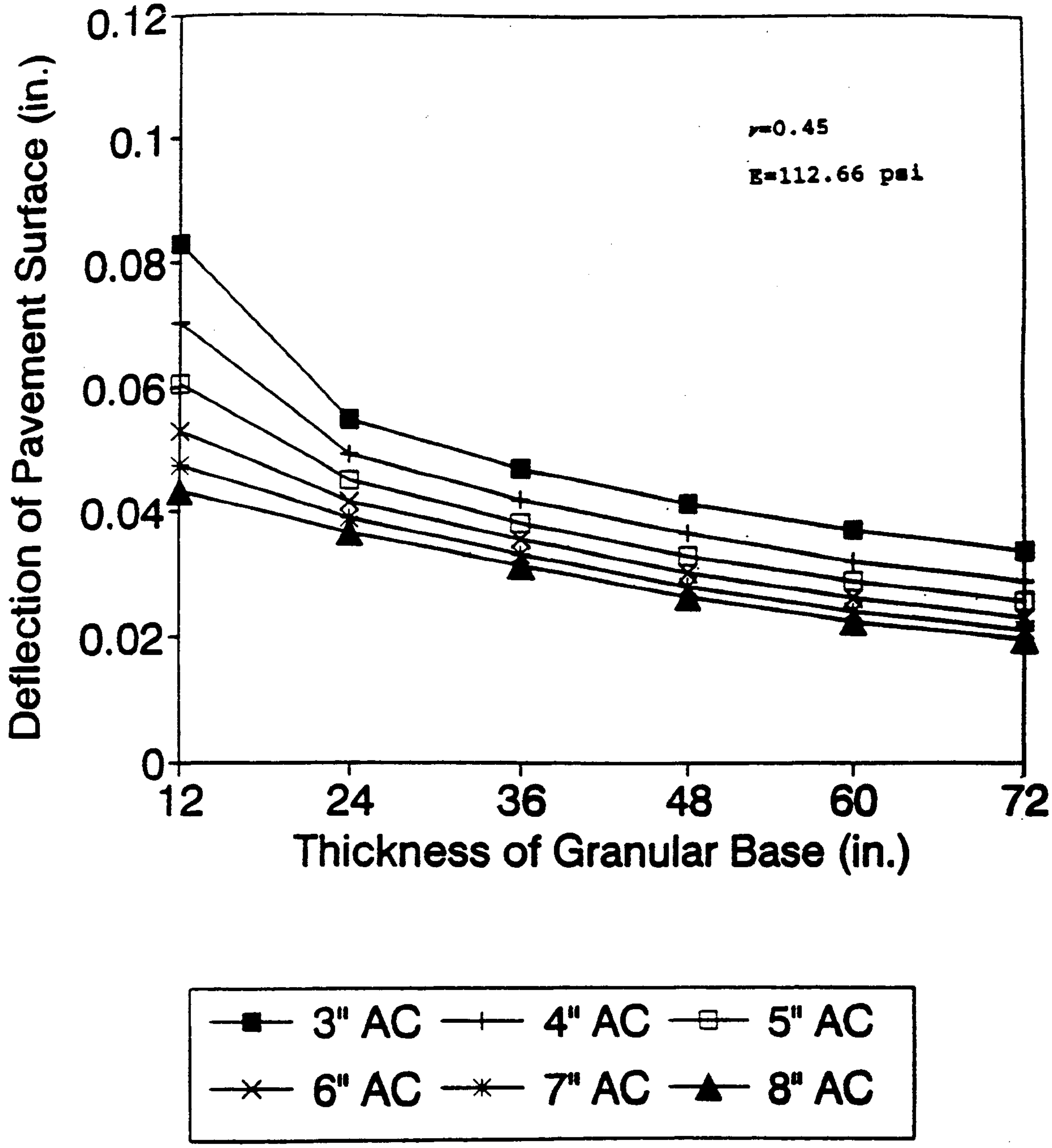


Fig. 66. Surface deflections as a function of asphalt concrete and granular base thickness for a 2-ft shredded tire layer (isotropic, elastic).

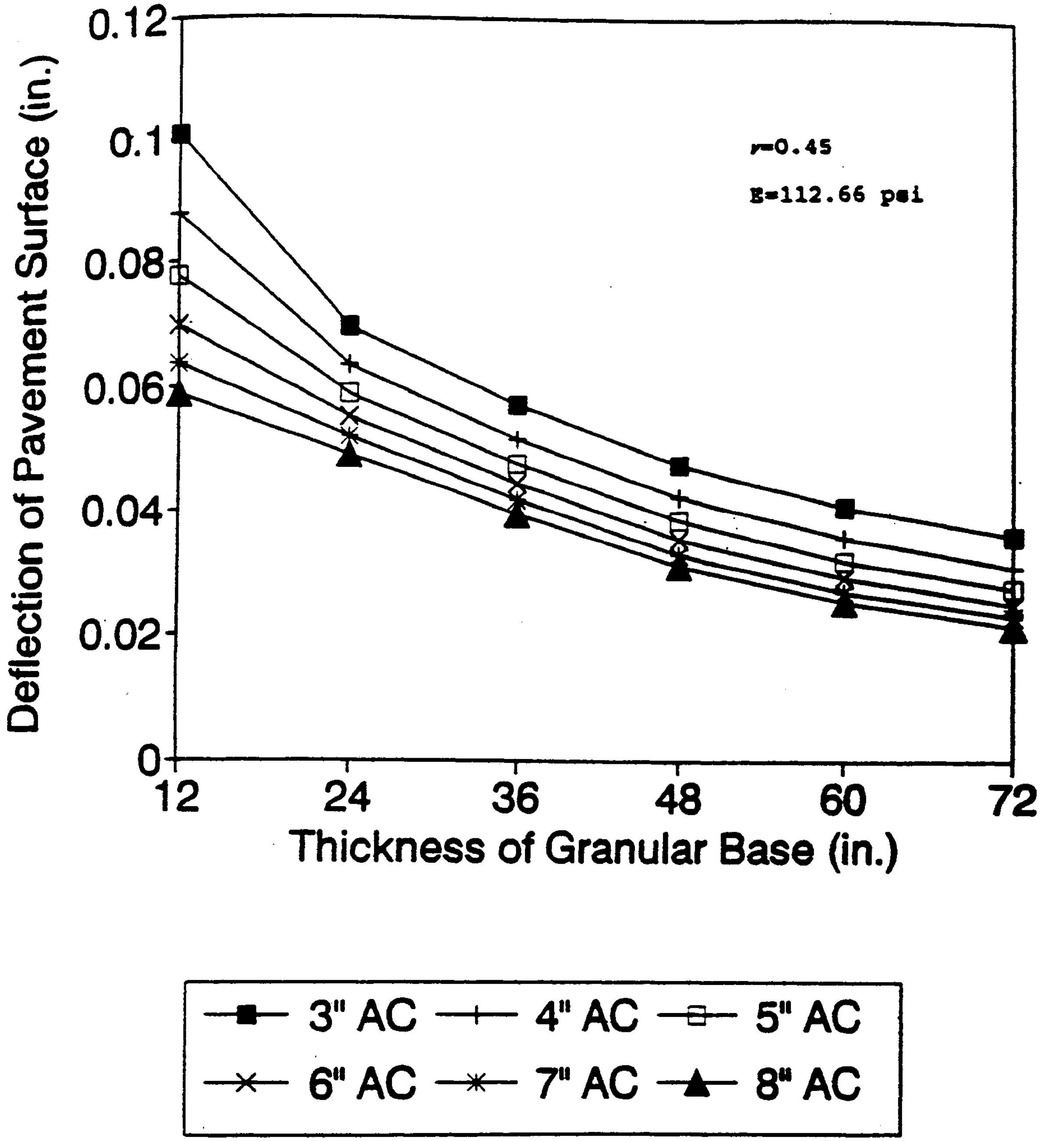


Fig. 67. Surface deflections as a function of asphalt concrete and granular base thickness for a 3-ft shredded tire layer (isotropic, elastic).

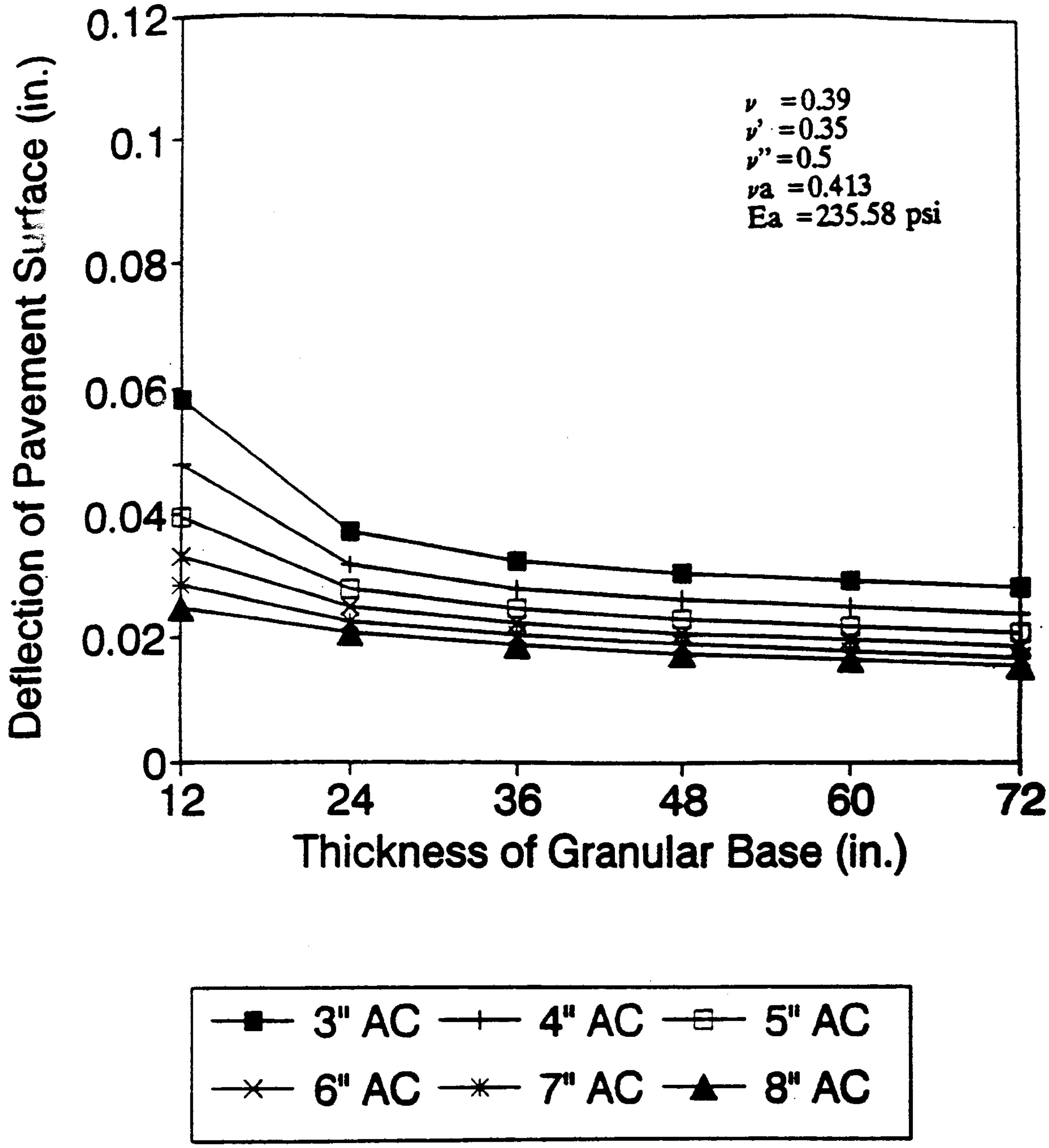


Fig. 68. Surface deflections as a function of asphalt concrete and granular base thickness for a 1-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.413, E_a = 235.58 psi).

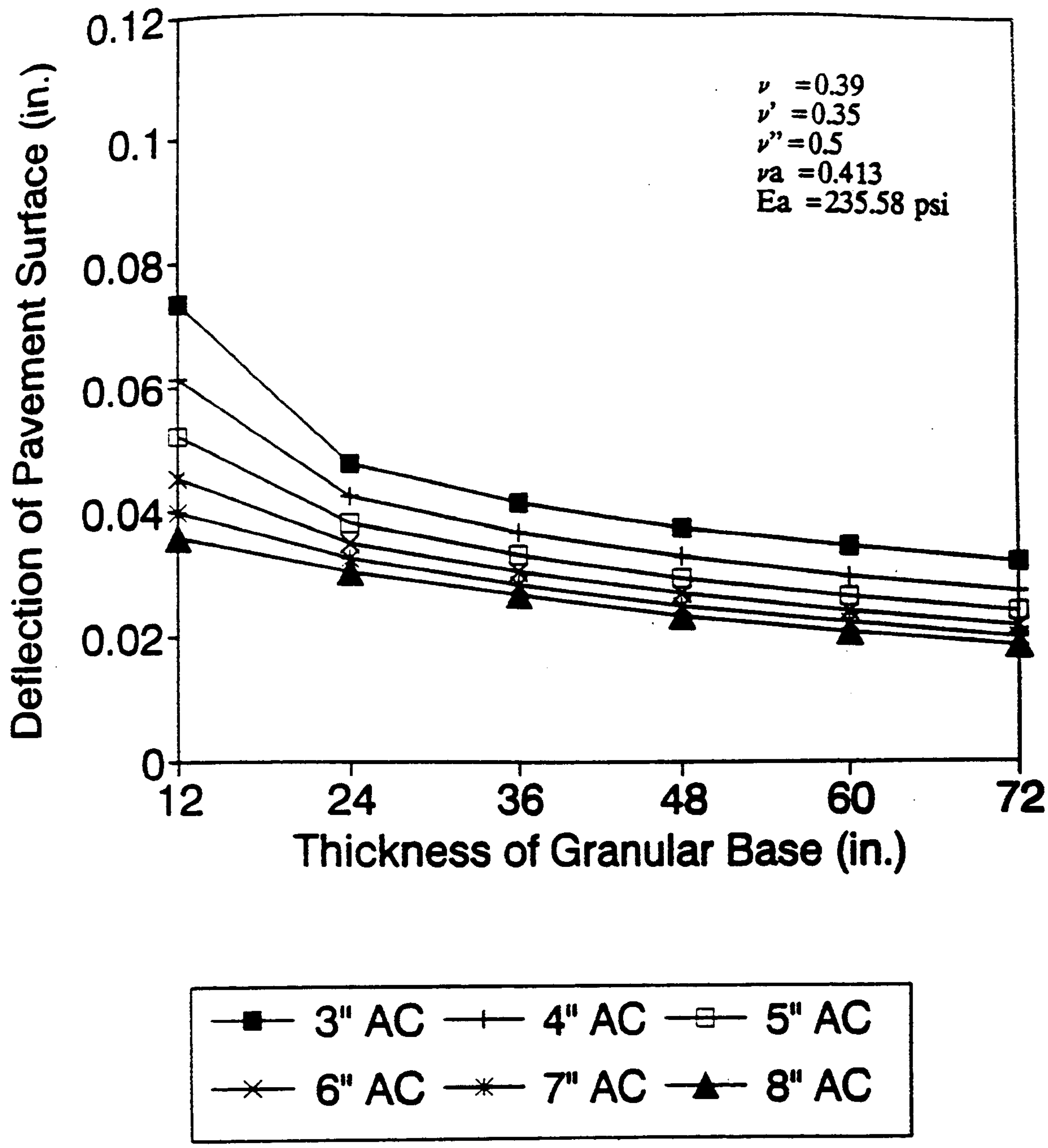


Fig. 69. Surface deflections as a function of asphalt concrete and granular base thickness for a 2-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.413, E_a = 235.58 psi).

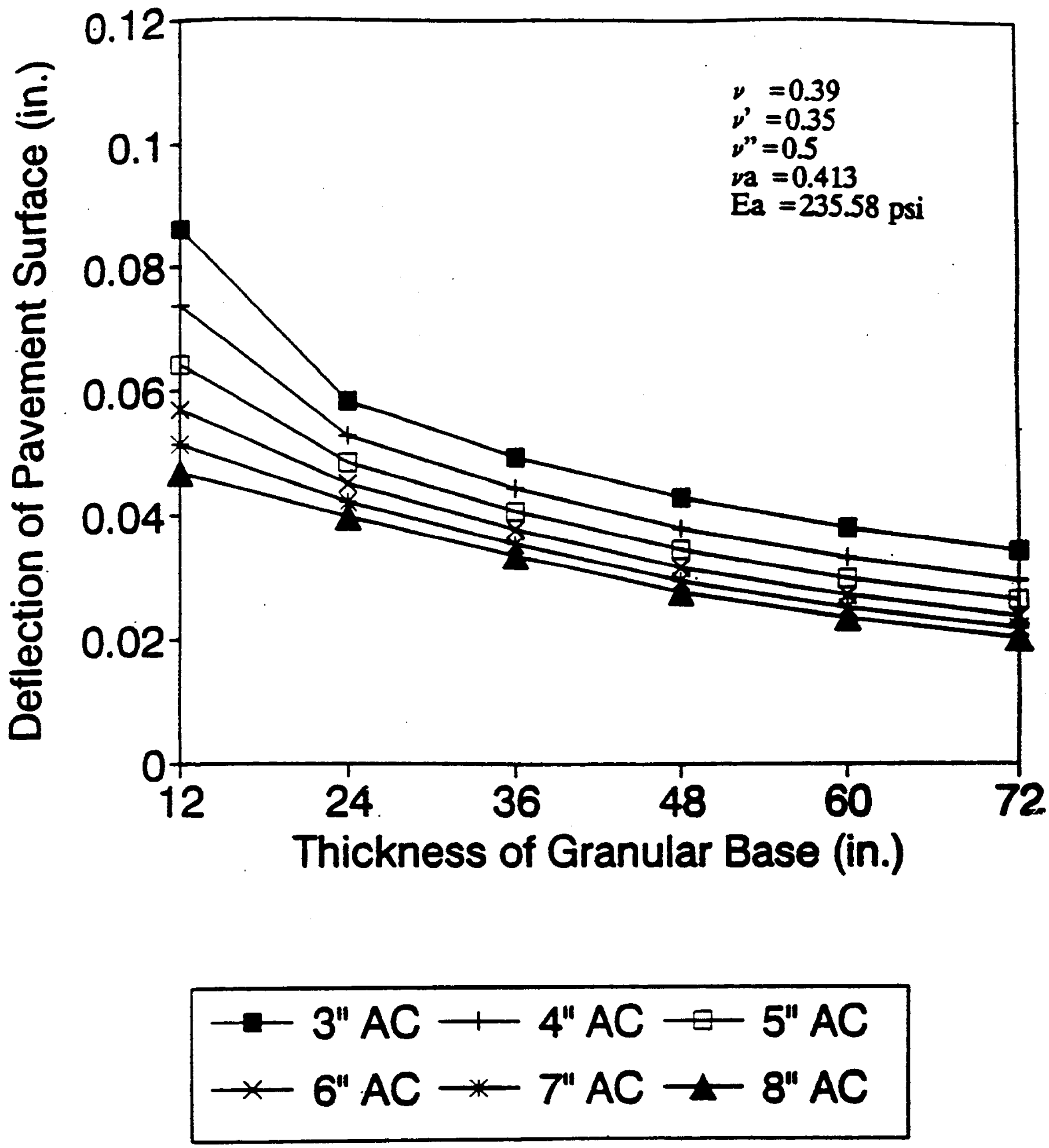


Fig. 70. Surface deflections as a function of asphalt concrete and granular base thickness for a 3-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.413, E_a = 235.58 psi).

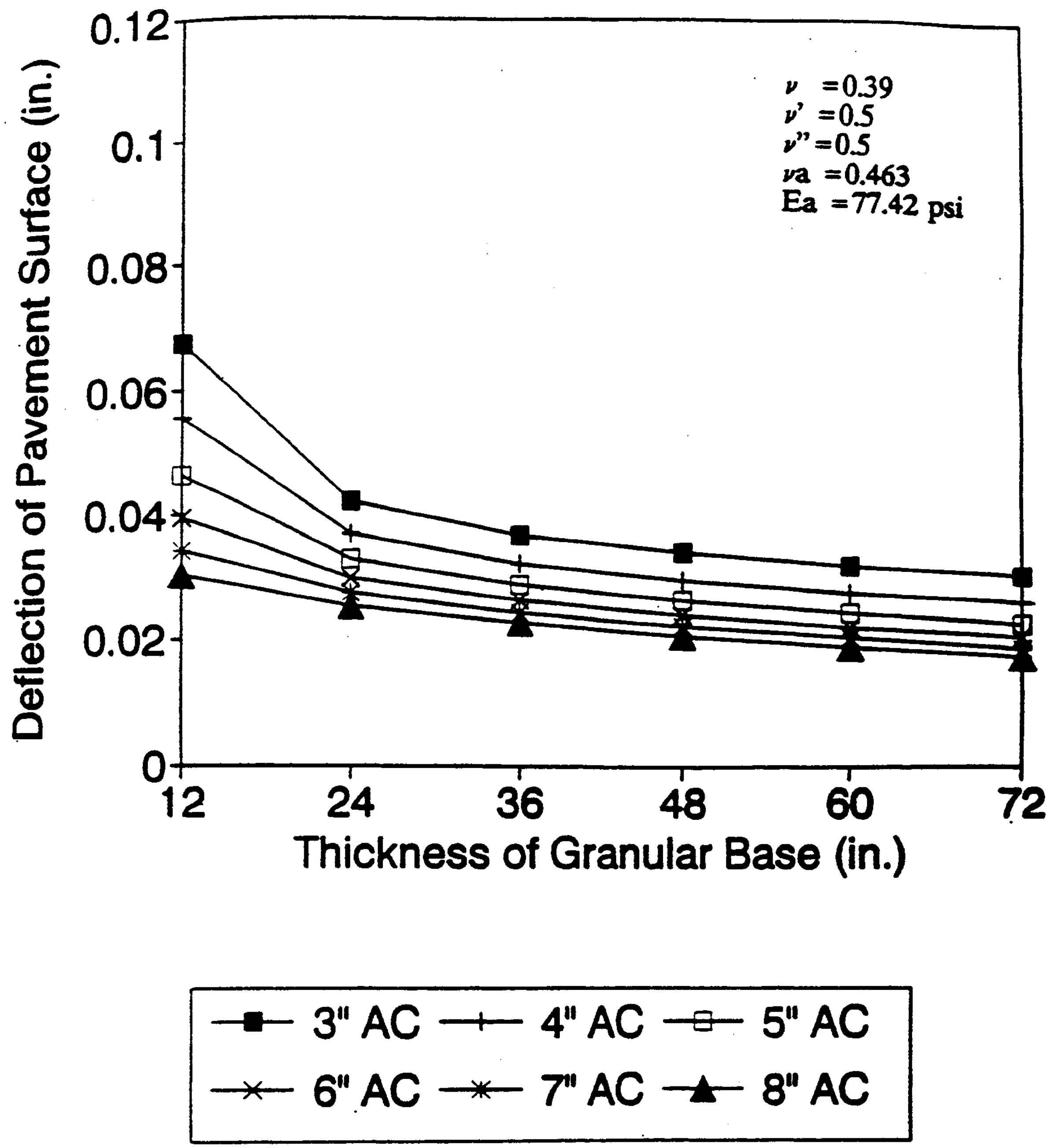


Fig. 71. Surface deflections as a function of asphalt concrete and granular base thickness for a 1-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.463, E_a = 77.42 psi).

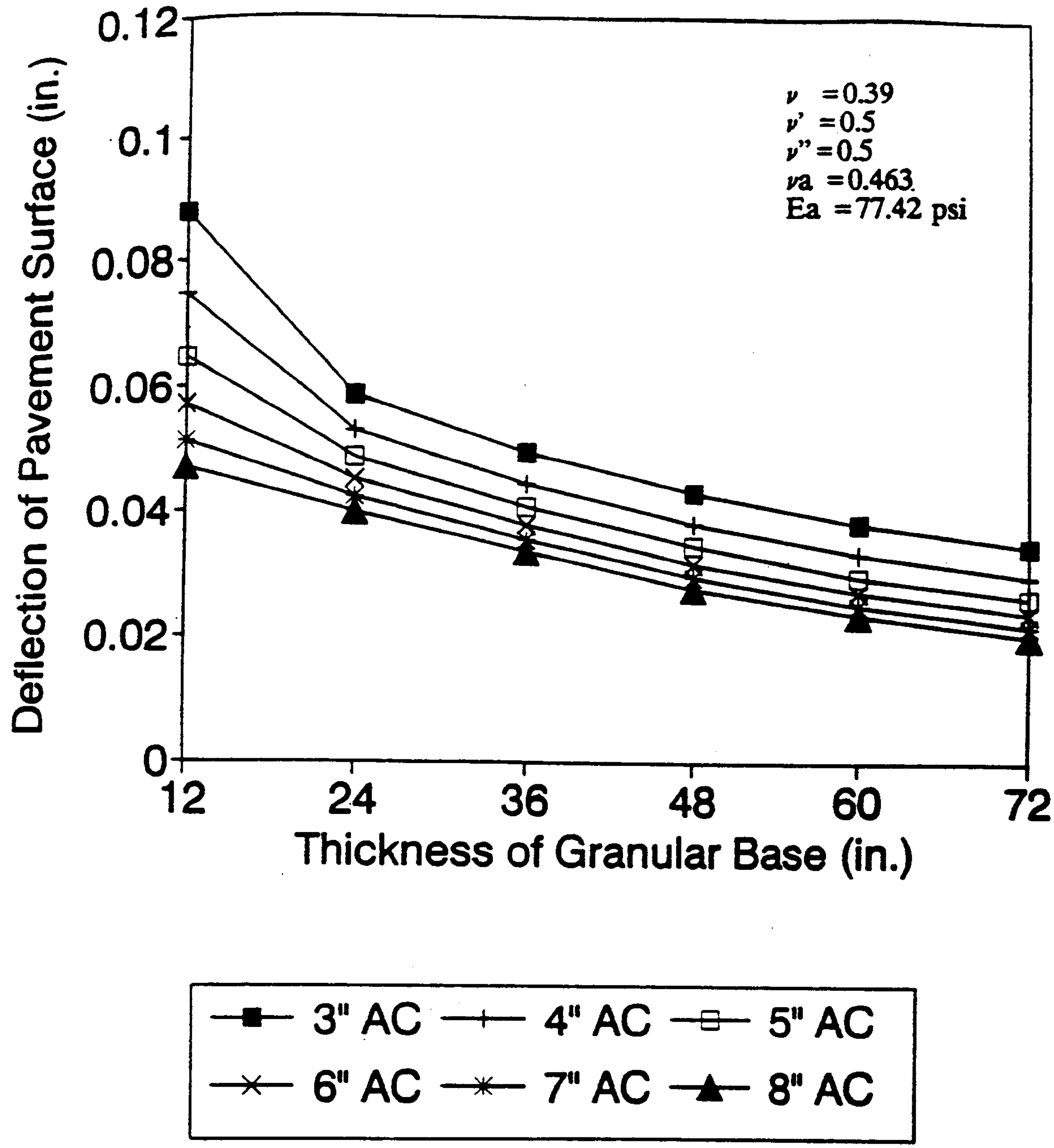


Fig. 72. Surface deflections as a function of asphalt concrete and granular base thickness for a 2-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.463, E_a = 77.42 psi).

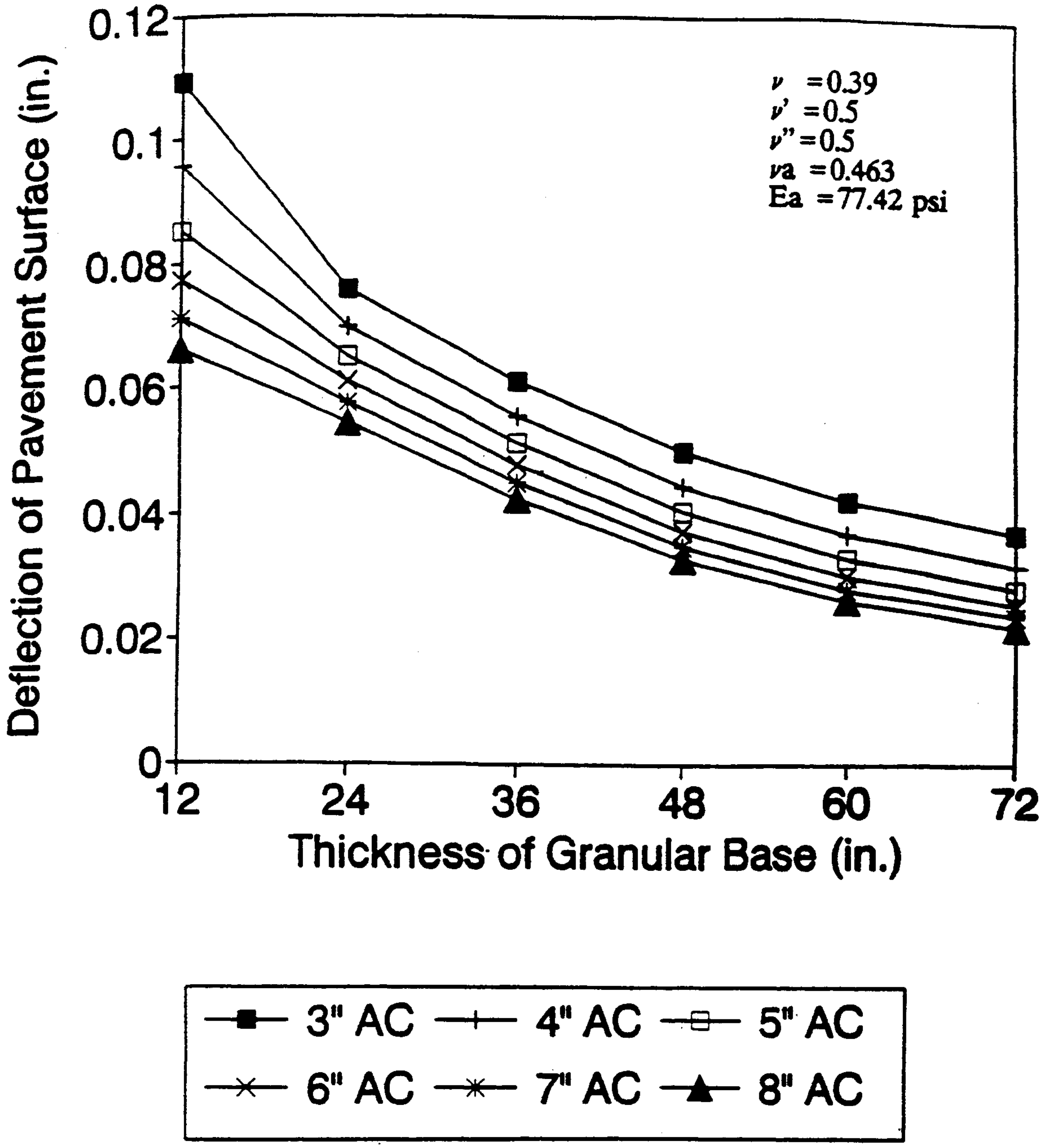


Fig. 73. Surface deflections as a function of asphalt concrete and granular base thickness for a 3-ft shredded tire layer treated as an anisotropic-transversely isotropic material approximated by isotropic properties (ν_a = 0.463, E_a = 77.42 psi).

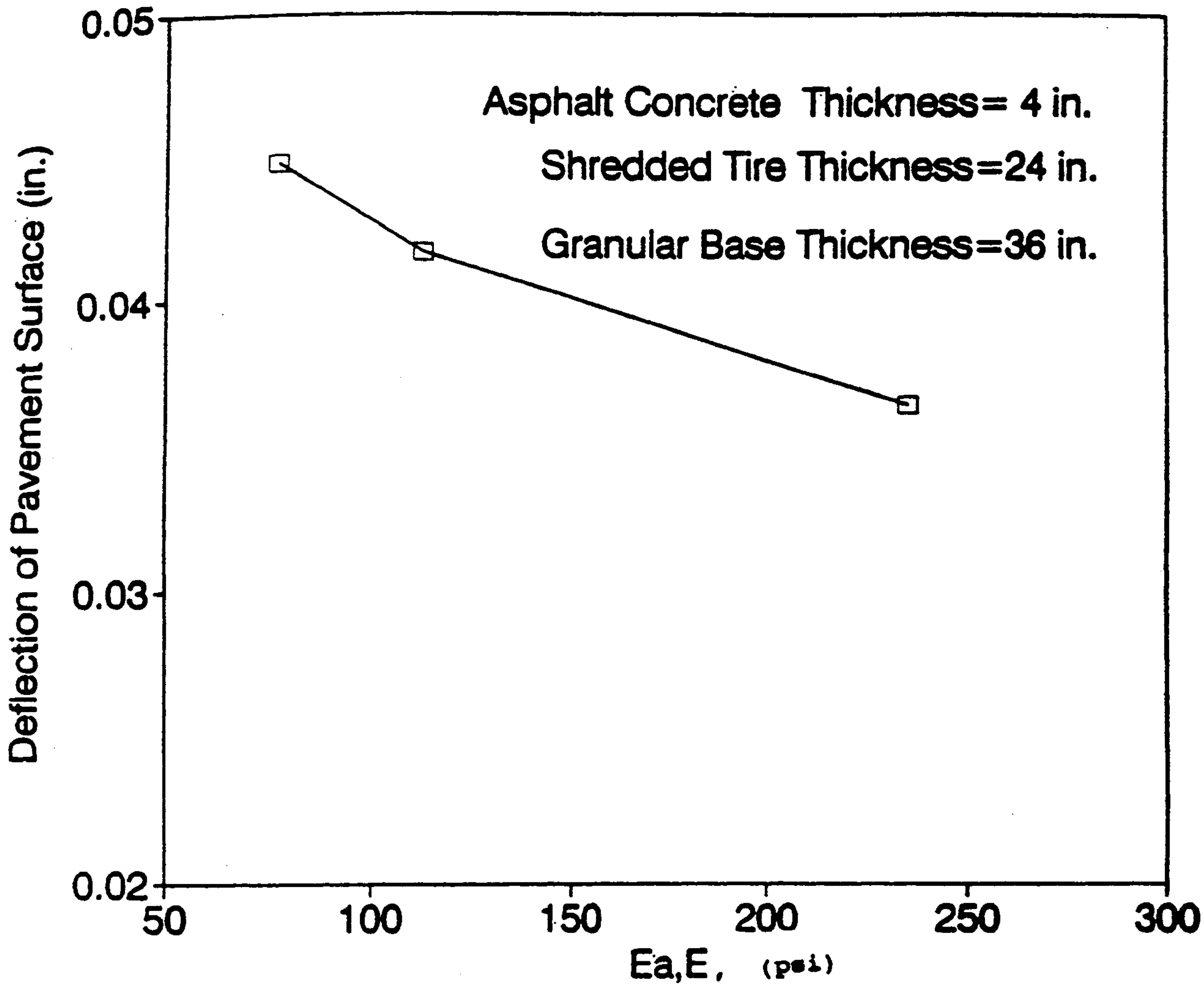


Fig. 74. Surface deflections as a function of E_a and E.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions derived from the literature review, selected Minnesota projects, and the laboratory tests conducted on shredded tires at the University of Minnesota.

CONCLUSIONS

Based upon the literature review the following conclusions can be made:

1) Using tire mats/shredded tires as lightweight fill can make an important contribution to utilizing the discarded tires that this nation produces.
2) Using tire mats as lightweight fill reduces the settlement and increases stability of embankments.
3) The low bulk unit weight ($\approx$20 lb/ft^3) of the tire mats served to limit the settlement of embankment constructed on compressible foundations.
4) Shredded tires can be used as reinforcement material. They can improve the strength properties of moderately plastic clay embankment soils by providing higher strength and smaller deformations prior to failure.
5) Including shredded tires (< 3 in.) in silty, plastic clay manifested an internal friction angle of about 23°, and cohesion of about 3 psi.
6) Shredded tires are free draining (permeability coefficient$\approx$10,000 ft/day) so there are no problems with build-up of excess pore pressure.

Based upon the projects initiated in Minnesota these following conclusions can be reached:

1) Most of the projects were contruction of emankments over highly compressible and very weak organic soils (peat,etc..).
2) In most projects the construction began with placement of geotextile fabric followed by placement of an initial lift of shredded tires. This procedure reduces the risk of embankment shear failure.

3) Shredded tire pieces with size ranging from 4 to 24 in. have an uncompacted bulk unit weight ranging from 15 to 30 lb/ft^3.

4) The effective number of a D7F-Caterpilar dozer passes on 3-ft layer of shredded tires with average particle area=144 in^2 to achieve effective compaction is about 8 to 12 passes.

5) A plate load test conducted on 4 in. maximum size of compacted shredded tires gave a low modulus of subgrade reaction (k) of about 2.8 pci.

6) The total settlement of an embankment constructed with shredded tire subgrade is about 50% less than that of an embankment constructed with granular subgrade.

7) Shredded tires are cheaper in many areas of the country where lightweight aggregate such as expanded shale is not available locally.

8) The angle of repose of shredded tires is about 45°.

9) The results of FWD tests showed large deflections, i.e., for a normalized 3000-lb vertical load, the maximum deflection was about 0.06 in.

Based upon the laboratory tests the following conclusions can be made:

1) One-dimensional compressibility test on shredded tires is a simple test to evaluate the compressibility indices of shredded tires.

2) Shredded tires (< 2 in.) have an uncompacted bulk unit weight of about 30 lb/ft^3, and a specific gravity of about 1.08.

3) Compressibility tests showed that at low levels of vertical stress (1-8 psi), the deflection of shredded tires is very high, however, it decreases significantly when the stress increases.

4) Horizontal stress varies bilinearly with the vertical stress on shredded tires.

5) The coefficient of lateral pressure (K) is about 0.49 at low vertical stress, and about 0.82 at high vertical stress. This coefficient can be used to determine the variation of lateral earth pressure with depth for a retaining wall.

6) The coefficient of compressibility in the laboratory is different from that in the field because e vs. log(p) curves are different in the two environment. In the laboratory environment, the compressibility index (C_c) is about 0.50, and the swelling index (C_s) is about 0.27. These indices can be used to determine approximately settlements of shredded tires in a way similar to that used in foundation analysis in geotechnics.

Based upon the elastic multilayer deflection analysis ELSYM5 the following conclusions can be made:

1) For evaluating the pavement system deflection using a multilayer elastic analysis ELSYM5 the elastic parameters of the shredded tires must be known. These can be evaluated by assuming the shredded tires as an isotropic elastic material or as an anisotropic-transversly isotropic elastic material approximated by a fictitious isotropic material.
2) If the shredded tires are regarded as an isotropic elastic material the elastic parameters are : Young's modulus E=113 psi, Poisson's ratio v=0.45.
3) If the shredded tires are regarded as an anisotropic-transversly isotropic elastic material approximated by a fictitious isotropic material the elastic parameters are: average Young's modulus E_a=68-2750 psi, average Poisson's ratio v_a=0.31 - 0.47.
4) The deflections for the anisotropic transversly isotropic material approximated by a fictitious isotropic material may be greater or smaller than for the isotropic material depending on the actual values of material constants.
5) The exact analysis of material anisotropy requires more elaborate tests than those conducted.
6) The exact analysis of deflections incorporating material anisotropy requires the use of an appropriate computer code.

RECOMMENDATIONS

Based on the study results the following recommendations can be made:

1) Different shredding process can produce different size shredded tires with highly varying characteristics. This is further complicated by the source of tires, i.e., automobile, truck, or tractor tire. Therefore, it is recommended to bring an order to physical characterization and classification of waste tire products.
2) A variety of detailed field tests should be conducted during construction using shredded tires, e.g., plate load test, FWD test, Benkelman beam test, etc., to monitor deflection prior to paving.
3) Compressibility tests should be conducted on compacted shredded tires samples.
4) Shredded tires can be used in unsurfaced roads with geotextiles and they can be also used behind retaining walls.
5) Caution should be used when placing a shredded tire layer below a hard surfaced road. Serious consideration should be given to the traffic volume of heavy vehicles and the amount of overburden to be used over the shredded tires. Excessive deflections may result under repeated heavy loads, fatigue damage may accumulate rapidly.
6) Future studies should investigate use of shreded tires as soil reinforcement.
7) The anisotropy of all pavement materials needs to be thoroughly investigated. The use of isotropy in the modelling of anisotropic materials can lead to significant errors in the prediction of pavement responses.

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APPENDIX A

LIGHTWEIGHT FILL SPECIFICATION [AFTER REF. 9]

1. The lightweight fill material shall consist of chipped or shredded tire pieces meeting the following specifications:

A. Eighty percent of the material (by weight) must pass a 6 in. screen.

B. A minimum of fifty percent of the material (by weight) must be retained on a 4 in. screen.

C. All pieces shall have at least one sidewall severed from the face of the tire.

D. The largest allowable piece is a quarter circle in shape or 12 in. length, whichever is lesser dimension.

E. All metal fragments shall be firmly attached and 98% embedded in the tire sections from which they were cut out. NO METAL PARTICLES WILL BE ALLOWED IN THE FILL WITHOUT BEING CONTAINED WITHIN A RUBBER SEGMENT. Ends of metal belts and beads are expected to be exposed only in the cut faces of some tire chips. If metal particles are found by the Contractor, they will be placed off to the side and the suppiler shall be called back to pick up this material along with any unused tire chips at no cost to the City.

F. The tire chips supplied shall be free of any contaminants such as oil, grease, etc., that could leach into the ground water.

G. The lightweight fill material supplied shall weigh less than 600 $lb/yard^3$ (by truck measure).

H. Unsuitable material delivered to the project will be rejected and it will be the supplier's responsibility to remove the material from the site at no cost to the City.

APPENDIX B

LABORATORY DATA

SHREDDED TIRES

	Sample no. 1	2	3
Sieve Opening (in)	Percent Passing		
2	100	100	100
1	20	24	45
0.75	9	10	20
0.5	1.3	2.6	7.3
0.25	0.67	1	3

Test no.1

VERT. LOAD (lbs)	VERT. DISPL. (in)	HOOP STRAIN (%)	VERT. STRESS (psi)	VERT. STRAIN (%)	HORIZ STRESS (psi)
0	0.00	0	0.00	0.00	0.00
280	0.68	1.56E-05	0.44	2.69	0.12
559.9	1.50	3.13E-05	0.88	5.89	0.25
1119.8	2.23	6.31E-05	1.77	8.75	0.50
1679.7	2.46	9.47E-05	2.65	9.68	0.75
2239.6	2.73	0.000125	3.54	10.73	0.99
2799.5	3.00	0.000158	4.42	11.78	1.24
3359.4	3.85	0.000188	5.30	15.14	1.48
3919.3	4.10	0.000221	6.19	16.13	1.73
4479.2	4.54	0.00025	7.07	17.83	1.98
6158.9	5.14	0.000347	9.72	20.19	2.72
6718.8	5.29	0.000375	10.61	20.81	2.97
8958.4	5.92	0.0005	14.14	23.27	3.96
9518.3	6.08	0.000536	15.03	23.89	4.21
12317.7	6.65	0.000688	19.44	26.13	5.44
12877.7	6.76	0.000719	20.33	26.58	5.69
13997.6	6.81	0.000789	22.10	26.77	6.19
16797.1	7.36	0.00156	26.52	28.94	12.35
17916.9	7.58	0.001868	28.28	29.8	14.79
19036.7	7.80	0.002175	30.05	30.65	17.22
20716.4	8.13	0.002748	32.70	31.97	21.76
23515.4	8.51	0.003462	37.12	33.47	27.41
26315.4	8.90	0.004176	41.54	34.99	33.07
30794.6	9.54	0.005423	48.61	37.49	42.94
32474.3	9.59	0.00588	51.26	37.71	46.56
36393.6	9.73	0.006948	57.45	38.23	55.01
26315.4	9.45	0.001193	41.54	37.13	33.19
19596.6	9.14	0.001154	30.94	35.91	20.05
14557.4	8.75	0.001105	22.98	34.38	10.08
11198.4	8.37	0.001057	17.68	32.89	5.79
7838.6	7.96	0.001005	12.37	31.27	4.03
5599	7.57	0.000956	8.84	29.74	3.08
3919.3	7.04	0.000889	6.19	27.66	2.10
3359.4	6.64	0.000838	5.30	26.08	1.61
7838.6	6.97	0.00088	12.37	27.38	5.78
10078.2	7.36	0.000929	15.91	28.92	7.44
13437.6	7.75	0.000978	21.21	30.45	9.93
16797.1	8.14	0.001028	26.52	31.98	16.52
20716.4	8.67	0.001094	32.70	34.06	24.21
25195.6	9.05	0.001142	39.77	35.56	33.00
30794.6	9.61	0.001213	48.61	37.76	43.99
36393.6	10.16	0.001283	57.45	39.92	55.32
28555	9.72	0.001227	45.08	38.19	38.69
20716.4	9.10	0.001149	32.70	35.75	23.06
15117.4	8.69	0.001097	23.86	34.14	11.67
11198	8.26	0.001043	17.68	32.45	5.98
8398.5	7.88	0.000995	13.26	30.96	4.83
6158.9	7.47	0.000943	9.72	29.35	3.74
3919.3	7.06	0.000891	6.19	27.74	2.50
3359.4	6.67	0.000842	5.30	26.20	1.77

Test no.2

VERT. LOAD (lbs)	VERT. DISPL. (in)	HOOP STRAIN (%)	VERT. STRESS (psi)	VERT. STRAIN (%)	HORIZ STRESS (psi)
0	0	0	0	0	0
280	0.86	4.35E-05	0.44	3.36	0.34
559.9	1.80	8.71E-05	0.88	7.07	0.69
1119.8	2.57	0.000174	1.77	10.09	1.38
1679.7	3.42	0.000261	2.65	13.46	2.07
2239.6	4.37	0.000349	3.54	17.16	2.76
2799.5	4.84	0.000435	4.42	19.03	3.44
3359.4	5.14	0.000522	5.30	20.19	4.13
3919.3	5.50	0.00061	6.19	21.61	4.83
4479.2	6.08	0.000696	7.07	23.89	5.51
6158.9	6.57	0.000958	9.72	25.81	7.59
6718.8	6.87	0.001045	10.61	27.01	8.27
8958.4	7.79	0.001393	14.14	30.62	11.03
9518.3	7.96	0.00148	15.03	31.29	11.72
12317.8	8.65	0.001916	19.45	33.98	15.17
12877.7	8.77	0.002003	20.33	34.49	15.86
13997.6	8.99	0.002177	22.10	35.32	17.24
16797.1	9.50	0.002823	26.52	37.35	22.35
17916.9	9.70	0.00309	28.28	38.11	24.47
19036.7	9.89	0.003358	30.05	38.87	26.59
20716.4	10.03	0.003784	32.70	39.43	29.96
23515.4	10.27	0.004382	37.12	40.38	34.70
26315.4	10.59	0.005065	41.54	41.61	40.11
32474.3	10.89	0.006508	51.26	42.79	51.53
36393.6	11.08	0.007427	57.45	43.55	58.81
26315.4	11.04	0.004355	41.54	43.38	34.49
19596.6	10.73	0.002696	30.94	42.16	21.35
14557.4	10.34	0.001437	22.98	40.63	11.38
11198.4	9.96	0.000895	17.68	39.14	7.09
7838.6	9.55	0.000673	12.37	37.52	5.33
5599	9.16	0.000553	8.84	35.99	4.38
3919.3	8.63	0.000429	6.19	33.91	3.40
3359.4	8.23	0.000367	5.30	32.33	2.91
7838.6	8.56	0.000894	12.37	33.63	7.08
10078.2	8.95	0.001103	15.91	35.17	8.74
13437.6	9.34	0.001418	21.21	36.70	11.23
16797.1	9.73	0.00225	26.52	38.23	17.82
20716.4	10.26	0.003221	32.70	40.31	25.51
25195.6	10.64	0.004331	39.77	41.81	34.30
30794.6	11.20	0.005719	48.61	44.01	45.29
36393.6	11.75	0.00715	57.45	46.17	56.62
28555	11.31	0.00505	45.08	44.44	39.99
20716.4	10.69	0.003076	32.70	42.00	24.36
15117.4	10.28	0.001638	23.86	40.39	12.97
11198	9.85	0.000919	17.68	38.70	7.28
8398.5	9.47	0.000774	13.26	37.21	6.13
6158.9	9.06	0.000636	9.72	35.60	5.04
3919.3	8.65	0.000479	6.19	33.99	3.80
3359.4	8.26	0.000387	5.30	32.45	3.07

Test no.3

VERT. LOAD (lbs)	VERT. DISPL. (in)	HOOP STRAIN (%)	VERT. STRESS (psi)	VERT. STRAIN (%)	HORIZ STRESS (psi)
0	0	0	0	0	0
280	1.11	3.13E-05	0.44	4.37	0.25
1119.8	1.97	0.000124	1.77	7.74	0.99
1679.7	2.82	0.000187	2.65	11.10	1.48
2239.6	3.30	0.00025	3.54	12.96	1.98
2799.5	3.77	0.000311	4.42	14.81	2.47
3359.4	4.06	0.000375	5.30	15.96	2.97
3919.3	4.35	0.000436	6.19	17.10	3.46
4479.2	4.71	0.0005	7.07	18.51	3.96
6158.9	5.42	0.000684	9.72	21.29	5.44
6718.8	5.56	0.00075	10.61	21.87	5.94
8958.4	6.26	0.001	14.14	24.6	7.92
9518.3	6.42	0.001058	15.03	25.24	8.41
12317.7	7.13	0.001375	19.44	28.04	10.89
12877.7	7.28	0.001438	20.33	28.60	11.38
13997.6	7.43	0.001556	22.10	29.19	12.37
16797.1	7.93	0.002195	26.52	31.17	17.38
17916.9	8.13	0.002451	28.28	31.97	19.41
19036.7	8.37	0.002691	30.05	32.90	21.31
20716.4	8.60	0.003075	32.70	33.81	24.35
23515.9	8.99	0.003714	37.12	35.33	29.41
26315.4	9.23	0.004332	41.54	36.29	34.30
30794.4	9.55	0.005288	48.61	37.54	41.87
32474.3	9.67	0.005647	51.26	38.02	44.71
36393.6	9.83	0.006604	57.45	38.63	52.29
26315.4	9.58	0.004043	41.54	37.64	32.02
19596.6	9.27	0.002384	30.94	36.42	18.88
14557.4	8.88	0.001125	22.98	34.89	8.91
11198.4	8.50	0.000583	17.68	33.40	4.62
7838.6	8.09	0.000361	12.37	31.78	2.86
5599	7.70	0.000241	8.84	30.25	1.91
3919.3	7.17	0.000117	6.19	28.17	0.93
3359.4	6.77	5.51E-05	5.30	26.60	0.44
7838.6	7.10	0.000582	12.37	27.89	4.61
10078.2	7.49	0.000791	15.91	29.43	6.27
13437.6	7.88	0.001106	21.21	30.96	8.76
16797.1	8.27	0.001938	26.52	32.49	15.35
20716.4	8.80	0.002909	32.70	34.58	23.04
25195.6	9.18	0.004019	39.77	36.07	31.83
30794.6	9.74	0.005407	48.61	38.27	42.82
36393.6	10.29	0.006838	57.45	40.43	54.15
28555	9.85	0.004738	45.08	38.70	37.52
20716.4	9.23	0.002764	32.70	36.27	21.89
15117.4	8.82	0.001326	23.86	34.65	10.50
11198	8.39	0.000607	17.68	32.96	4.81
8398.5	8.01	0.000462	13.26	31.47	3.66
6158.9	7.60	0.000324	9.72	29.86	2.57
3919.3	7.19	0.000167	6.19	28.25	1.33
3359.4	6.80	7.53E-05	5.30	26.71	0.60

Table 7. Average of Test Results

VERT. LOAD P_{zz} (lbs)	VERT. DISPL. u_z (in)	HOOP STRAIN $\epsilon_{\theta\theta}$ (%)	VERT. STRESS σ_{zz} (psi)	VERT. STRAIN ϵ_{zz} (%)	HORIZ. STRESS $\sigma_{xx}=\sigma_{yy}$ (psi)
0	0	0	0	0	0
280	0.88	3.03E-05	0.44	3.46	0.24
559.9	1.56	6.06E-05	0.88	6.13	0.48
1119.8	2.25	0.00012	1.77	8.84	0.95
1679.7	2.9	0.000181	2.65	11.40	1.43
2239.6	3.46	0.000241	3.54	13.60	1.91
2799.5	3.87	0.000302	4.42	15.21	2.39
3359.4	4.35	0.000361	5.30	17.10	2.86
3919.3	4.65	0.000422	6.19	18.28	3.34
4479.2	5.11	0.000482	7.07	20.09	3.82
6158.9	5.71	0.000663	9.72	22.44	5.25
6718.8	5.91	0.000724	10.61	23.23	5.73
8958.4	6.66	0.000965	14.14	26.18	7.64
9518.3	6.82	0.001024	15.03	26.81	8.11
12317.8	7.48	0.001326	19.44	29.40	10.5
12877.7	7.6	0.001387	20.33	29.87	10.98
13997.6	7.74	0.001508	22.10	30.42	11.94
16797.1	8.26	0.002192	26.52	32.47	17.36
17916.7	8.47	0.00247	28.28	33.29	19.56
19036.7	8.68	0.002742	30.05	34.12	21.71
20716.4	8.92	0.003189	32.70	35.06	25.25
23515.4	9.26	0.003853	37.12	36.40	30.51
26315.4	9.57	0.004524	41.54	37.62	35.82
30794.6	9.96	0.00565	48.61	39.15	44.74
32474.3	10.05	0.006068	51.26	39.50	48.05
36393.6	10.21	0.006993	57.45	40.13	55.37
26315.4	10.02	0.004197	41.54	39.39	33.23
19596.6	9.71	0.002537	30.94	38.17	20.09
14557.5	9.32	0.001278	22.98	36.64	10.12
11198.4	8.94	0.000736	17.68	35.14	5.83
7838.6	8.53	0.000514	12.37	33.53	4.07
5599	8.14	0.000394	8.84	32.00	3.12
3919.3	7.61	0.00027	6.19	29.91	2.14
3359.4	7.21	0.000208	5.30	28.34	1.65
7838.6	7.54	0.000734	12.37	29.64	5.82
10078.2	7.93	0.000944	15.91	31.17	7.48
13437.6	8.32	0.001259	21.21	32.70	9.97
16797.1	8.71	0.002092	26.52	34.24	16.56
20716.4	9.24	0.003063	32.70	36.32	24.25
25195.6	9.62	0.004173	39.77	37.81	33.04
30794.6	10.18	0.00556	48.61	40.02	44.03
36393.6	10.73	0.006992	57.45	42.18	55.36
28555	10.29	0.004891	45.08	40.45	38.73
20716.4	9.67	0.002917	32.70	38.01	23.1
15117.4	9.26	0.001479	23.86	36.40	11.71
11198	8.83	0.00076	17.68	34.71	6.02
8398.5	8.45	0.000615	13.26	33.22	4.87
6158.9	8.04	0.000477	9.72	31.60	3.78
3919.3	7.63	0.000321	6.19	29.99	2.54
3359.4	7.24	0.000229	5.30	28.46	1.81

WOOD CHIPS

Sieve Opening (in)	Percent Passing
2	100
1	60
0.75	35
0.5	10
0.25	3

VERT. LOAD (lbs)	VERT. DISPL. (in)	HOOP STRAIN (%)	VERT. STRESS (psi)	VERT. STRAIN (%)	HORIZ STRESS (psi)
0	0	0	0	0	0
1735.696	0.51	0.000123	2.74	2	0.98
3471.393	1.02	0.000246	5.48	4	1.95
4339.241	1.27	0.000308	6.85	5	2.44
8678.481	2.54	0.000616	13.70	10	4.88
22396.08	3.56	0.001772	35.35	14	14.03
72787.26	5.09	0.004819	114.90	20	38.16
115843.7	5.60	0.007645	182.87	22	60.53
174171.5	6.11	0.012051	274.95	24	95.42
208196.1	6.36	0.013907	328.66	25	110.12
245461	6.61	0.018329	387.49	26	145.13
285966.4	6.87	0.021552	451.43	27	170.65
329712.3	7.12	0.020867	520.49	28	165.23
376698.7	7.38	0.028417	594.66	29	225.01
169287.9	7.12	0.010638	267.24	28	84.23
44841.55	6.87	0.002547	70.79	27	20.17
13729.95	6.74	0.000826	21.67	26.5	6.54
3359.41	6.61	0.000155	5.30	26	1.23