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Use of scrap tires in civil engineering applications

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Use of scrap tires in civil engineering applications

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TABLE OF CONTENTS

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ABSTRACT

Using scrap tires as construction materials in civil engineering is of growing interest. Whole scrap tires have been used as culverts, retaining walls, and for slope and beach stabilization. Shredded tires have been used as horizontal drains, ravine crossings, highway embankments, lightweight backfill, and road bed support. The practice of these applications needs the engineering properties of scrap tires. This dissertation involves the quantification of the structural and hydraulic properties of whole truck tires as underground culverts, the derivation of a new stress-strain relationship for low-stiffness flexible pipes and its application to a truck tire culvert, and the investigation and integration of the mechanical properties of shredded tire material. The design guidelines for truck tire culverts developed in this research are also included.

CHAPTER 1. GENERAL INTRODUCTION

Introduction

The Scrap Tire Management Council (1999) estimated that 266,000,000 scrap tires were added to the 800,000,000 existing scrap tires in stockpiles and dumps in 1996. Among them only 202,000,000 were reused or recycled. The increasing scrap tire stockpiles are posing serious environmental and health problems to the public. These problems include tire-related fires and diseases related to mosquitoes and rats found at the tire stockpile sites. These scrap tire problems will continue to grow until more scrap tires find environmentally sound and cost efficient markets.

Using scrap tires as construction materials in civil engineering is of growing interest (Blumenthal, 1997). In the past decade, shredded tires have been used to replace soils or gravel in many applications such as leachate collection systems, landfill covers, retaining wall backfill, road embankments, and road bed support (Humphrey et al., 1993; Bosscher et al., 1993; Lee et al., 1999; Masad et al.,1996; Blumenthal, 1997). These applications use tire chips typically less than 100 mm in size and involve the expensive tire-shredding process and hence are limited in practice (Kjartanson, et al., 1998). Since the beginning of 1996, three more cost-effective alternatives to recycle scrap tires in civil engineering drainage structures have been under investigation at Iowa State University (Kjartanson et al., 1998a and 1998b). These studies involve utilizing whole scrap tires and large tire shreds (300 – 1000 mm) in engineered drainage systems. The advantages of using whole tires and large tire shreds over gravel and small tire chips are greater economy and better performance (Kjartanson, et al., 1998). For example, the cost is $6.62/kN for tire shreds of 50 mm in size, and is $1.22/kN for tire shreds of 500 mm in size. The cost of shredded tire product increases exponentially as tire shred size decreases (Kjartanson, et al., 1998). Three drainage structures that reuse scrap tires were investigated at Iowa State University. The structures included:

- using whole scrap tires as an underground culvert,
- using large shredded tires as a horizontal drain, and
- using large shredded tires as a ravine crossing

The objectives of this project are to characterize the engineering properties of the scrap tires relevant to these applications and develop design guidelines for building drainage structures with scrap tires. This dissertation involves all the three areas of the project but focuses on the application of using whole scrap tires as an underground culvert.

Although some private companies have successfully built whole truck tire culverts (Kjartanson, et al., 1998), the engineering properties and the design and performance of scrap tire culverts have not been quantified. The purposes of this research were to characterize the engineering properties of whole truck tires relevant to their use as underground conduits, and develop design guidelines. The structural performance of scrap tire culverts was evaluated, and the hydraulic capacity of scrap tire culverts was analyzed. The design guidelines were developed based on the results obtained from the laboratory experiments, field tests, and theoretical analyses.

Dissertation organization

The alternative format is used for this dissertation. Four papers associated with scrap tire applications in civil engineering are presented here.

Chapter 1 is a general introduction.

Chapter 2 is a paper entitled "Scrap Tire Culverts: Hydraulics and Design" and is to be published in a TRB record. This paper discusses the hydraulic aspect of scrap tire culverts. The flow capacities of scrap tire culverts at various conditions were obtained.

Chapter 3 is a paper entitled "Scrap Tire Culverts: Structural Performance" and is to be submitted to the Canadian Geotechnical Journal. This paper discusses the strength and stiffness properties of scrap tires and the soil-structure interactions of scrap tire culverts. Maximum and minimum soil covers at different backfill conditions were obtained throughout CANDE computer program analysis.

Chapter 4 is a paper entitled "Laboratory Determination of Young's Modulus for Low-Stiffness Flexible Pipes" and is to be submitted to the ASTM Geotechincal Testing Journal. This paper describes the derivation of a new equation governing the load-deflection relationship of low stiffness flexible pipes and it's application to scrap tire culverts.

Chapter 5 is a paper entitled "Mechanical Properties of Tire Shreds" and is to be submitted to the ASTM Geotechincal Testing Journal. This paper presents the test results of the mechanical properties of tire chips and synthesizes the shear strength and elastic Young's modulus of tire chips from direct shear test and triaxial test results obtained by different studies.

Chapter 6 is a general conclusion.

The appendix entitled "Design Guidelines for Truck Tire Culvert" is the guidelines for designing truck tire culverts developed in this study. These design guidelines were included in the reports (Kjartanson et al., 1998a and 1998b) submitted to the sponsors of this project.

Literature review

Whole scrap tires as underground culverts

The concept of using whole scrap tires as underground conduits was generated and practiced by different agencies. In the early 1990s, the Louisiana Transportation Research Center (Cumbaa, 1994) conducted a simple feasibility study of utilizing scrap tires in roadside ditches. Whole scrap tires were placed side to side to form a conduit. Large-sized tire shreds were placed beside and on top of the tires, followed by stones with a geo-fabric in between. The constructed culvert was able to support a light truck and was observed to have good drainage characteristics with negligible head loss during moderate rains. However, Cumbaa (1994) did not quantitatively study the hydraulic and structural characteristics of the scrap tire culvert.

In the spring of 1995, Dodger Enterprises of Fort Dodge, Iowa constructed a 330-m long truck tire culvert to lower the groundwater level and to divert surface water runoff away from its building during the summer time. Although this culvert, built with whole scrap tires and tire shreds, has functioned satisfactorily, the design and performance aspects have not been determined quantitatively.

Another type of scrap tire pipe involves stacking, compressing and binding tire beads and sidewalls. Gattis and Everett (1996) conducted field performance evaluations of this type of culvert at about 30 sites in Oklahoma, Arkansas, and Texas. The investigations indicated that the tire pipe works well in many situations, but the manufacturing process and the difficulty of installation increase the cost and limit its applications.

The examples described above demonstrate an innovative use of scrap tires. However, to encourage wider application of scrap tire culverts, the design and performance issues need to be further investigated. The first three papers presented in this dissertation include a quantitative study of the structural performance and hydraulic analyses of whole scrap tire culverts. The results from field investigations, laboratory tests, and theoretical analyses, are the basis of the design guidelines for scrap tire culverts, which are included as an appendix.

Shredded tires as a construction material

The application of tire shreds as a horizontal drain, a ravine crossing, lightweight backfill, and in a road embankment requires the engineering properties of the shredded tire material. The engineering properties of shredded tires associated with these applications have been investigated by a number of researchers. Bernal (1996) conducted intensive literature review of the laboratory studies on tire shreds and tire chips. Humphrey et al. (1993), Foose et al. (1996), and Gebhardt (1997) conducted independent direct shear tests on tire shreds in large-size shear machines. The sizes of the materials they tested varied from 38 mm to 1400 mm. Using peak shear stress or, stress at a horizontal displacement equal to 10% or 9% of the length of the shear box if no peak stress is observed, as a failure criterion, the shear strength parameters were obtained. The friction angles obtained from these studies ranged from 19^0 to 38^0 with zero or a small cohesion intercept up to 11.5 kPa.

Bressette (1984), Ahmed (1993), Benda (1995), Masad et al. (1996), Wu et al. (1997) and Lee et al. (1999) conducted independent triaxial tests on tire chips. The sizes of the materials they tested were from 2mm to 38mm. All the tests were conducted at a compression loading mode except Wu et al. (1997), which conducted compression unloading tests. A linear stress-strain response was observed from all compression loading tests. Due to the variation of confining pressure and the difference of testing mode (compression loading or unloading), the results from these studies varied significantly. The friction angle ranges from 6^0 to 57^0, and the cohesion intercept varies from 0 to 82 kPa.

All the studies mentioned above used traditional soil mechanics direct shear and triaxial testing methods to quantify the shear strength of tire chips. The results were also analyzed using traditional Mohr-Coulomb failure envelope except Gebhardt (1997), who suggested a nonlinear power function. Due to the large range of confining pressure and particle sizea of the material, and the difference in sample unit weight, the shear strength parameters generated from different authors vary significantly.

The objective of this study was to conduct independent direct shear tests and triaxial tests of shredded tire material, examine the existing data of the shear strength of tire chips, and find a unified method to quantify the shear strength of tire chips.

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CHAPTER 2. SCRAP TIRE CULVERTS: HYDRAULICS AND DESIGN

A paper to be published in a TRB record

Shiping Yang, Bruce H. Kjartanson, Ruochuan Gu, and Robert A. Lohnes

ABSTRACT Reusing whole scrap tires as a culvert is a cost-effective alternative to drain water from small drainage basins. The complete design of a scrap tire culvert must consider both structural and hydraulic performance. This paper focuses on hydraulic considerations.

The hydraulic capacity of a scrap tire culvert is largely affected by the limited size and the relatively rough barrel formed by scrap tires. In this analysis, the hydraulic capacities of culverts made of truck tires, at various slopes and lengths, were obtained by estimating Manning's roughness coefficient and limiting the maximum flow depth in the culvert to 75% of the pipe diameter. The Manning's roughness coefficient of a truck tire culvert was estimated to be 0.05 and 0.075 with and without sand ballast placed in the bottom of tires, respectively. The results show that a truck tire culvert can drain water up to 0.35-m^3/s, and its hydraulic efficiency approaches that of conventional pipes of the same diameter when the slope is greater than 0.11 or 0.30 for culverts made of truck tires with or without sand ballast, respectively. The equivalent concrete and corrugated metal pipe sizes were obtained for corresponding flow capacities of truck tire culverts.

Keywords: Scrap tires, culvert, pipe, hydraulics, design, equivalent pipe size

INTRODUCTION

A culvert constructed of whole scrap tires is a novel solution to disposal of tires and an economical alternative to roadway water drainage. While some private companies have successfully built whole truck tire culverts (*1*), the engineering properties and the design aspects of scrap tire culverts have not been quantified. A study to quantify the structural and hydraulic characteristics of whole scrap tires as an underground conduit material was conducted by Kjartanson, et al. (*1*). This paper discusses only the hydraulic characteristics and the hydraulic design of scrap tire culverts.

The basic equation used to estimate the culvert flow is Bernoulli's equation:

$$H+\frac{V_u^2}{2g}=K_e\frac{V^2}{2g}+K_f\frac{V^2}{2g}+K_o\frac{V^2}{2g}+\frac{V_d^2}{2g} \qquad (1)$$

where H is the total head difference between the headwater and tailwater, V is the average velocity of flow in the culvert, V_u is the upstream approaching velocity, V_d is the downstream tailwater velocity, K_e is the coefficient of entrance head loss, K_f is the coefficient of friction head loss, K_o is the coefficient of outlet head loss, and g is the gravitational acceleration.

The terms associated with V_u and V_d in equation (1) can be dropped out because the cross sectional area at both the upstream and downstream ends is usually larger than the cross sectional area of the culvert itself, and the V_u and V_d

terms are usually negligible compared with the V terms. Furthermore, V_u and V_d can be very similar in magnitude and will cancel out in the equation. For a scrap tire culvert, the entrance head loss and outlet head loss are negligible compared with the friction head loss which is caused by the very rough barrel formed by tires. Consequently, equation (1) is simplified to:

$$H = K_f \frac{V^2}{2g} \quad . \tag{2}$$

Equation (2) implies that the barrel surface friction consumes all the energy of the flow in a scrap tire culvert.

ESTIMATION OF MANNING'S ROUGHNESS COEFFICIENT

To the knowledge of the authors, no tests have been performed to measure the Manning's coefficient of scrap tire culverts. The Manning's coefficient was estimated by empirical equations.

The friction head loss, h_f, is often expressed by the Darcy-Weisbach equation (2):

$$h_f = f \frac{L}{d} \frac{V^2}{2g} \tag{3}$$

where L is the length of the culvert, d is the pipe diameter which is set equal to 0.53-m for a truck tire culvert (the smallest measured inside diameter of 37 truck tires (*1*)), and f is the friction factor and is related to the roughness of the pipe.

From equations (2) and (3), K_f is equal to fL/d.

For the flow in a scrap tire culvert, applying the Manning's equation

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{4}$$

where n is the Manning's roughness coefficient, R is the hydraulic radius or the flow area divided by the wetted perimeter, and S is the hydraulic gradient of the flow.

The friction factor f can then be expressed in terms of Manning's roughness coefficient, n, by comparing equation (3) with equation (4):

$$f = 78.5 \frac{n^2}{R^{\frac{1}{3}}} \cdot \tag{5}$$

Generally, the friction factor f is a function of the Reynolds number of flow and the pipe roughness. When pipe roughness predominates, such as in a scrap tire culvert, the flow tends to be turbulent and the friction factor does not vary with the Reynolds number as indicated in the Moody diagram (*3*). This is expressed by the Nikuradse equation (*4*):

$$f = \frac{1}{(1.14 - 2\log\frac{k_s}{d})^2} \tag{6}$$

where k_s is the diameter of uniform grains which could be coated on a smooth pipe of the same diameter as the pipe under consideration and would cause the same friction head loss as the actual pipe. The ratio k_s /d is called the relative roughness of the pipe.

From equations (5) and (6), the roughness coefficient of a scrap tire culvert, n, can be calculated after k_s is estimated. An accurate estimation of k_s needs laboratory tests and experience. Due to the relatively high roughness of tire culvert barrel, a large k_s is expected.

Assuming k_s = 0.3-m for truck tire culverts, f is calculated from equation (6) to be 0.374. R is a function of the flow depth. From equation (5) a larger R would give a larger n when the f value is fixed, so the maximum R for a circular pipe, which is 0.304d (*2*), was used to calculate n. Substituting f=0.374 and R=0.304d into equation (5) gives an n value of 0.05. Incidentally, this value is twice the roughness coefficient of corrugated metal pipes.

The method proposed herein is an approximate estimation of the Manning's coefficient for scrap tire culverts. The eddy effect, which is caused by the turbulence of the flow in the tires, was not considered. As a result n might be underestimated. However, as sand ballast has been recommended for truck tire culverts to reduce the amount of water stagnating in the tires and mitigate buoyancy effects (*5*), the inside roughness and eddy effect are also reduced. Therefore, n = 0.05 is recommended for truck tire culverts with sand ballast. For truck tire culverts without sand ballast, a higher n value of 0.075 is recommended. This value is three times the roughness coefficient of corrugated metal pipes.

Because of the uncertainty associated with the roughness coefficient, it is recommended that the maximum flow depth in a scrap tire culvert be limited to less than 75% of the pipe diameter, or 0.4-m for a truck tire culvert. This constraint also helps to avoid buoyancy effects by air trapped in the tops of the tires.

DETERMINATION OF FLOW TYPES

There are two major conditions of culvert flow: flow with inlet control and flow with outlet control (*6*). For culverts with inlet control, the flow capacity is controlled at the entrance and is not affected by hydraulic factors beyond the condition of the culvert entrance. The water can flow through the pipe at a greater rate than it can enter. For outlet control, the culvert's hydraulic performance is determined by factors governing inlet control plus the tail-water depth, slope, length, and roughness of the culvert.

Either inlet control or outlet control can occur for both full flow and partly full flow in a culvert. For a scrap tire culvert, however, the maximum water depth has been limited to 75% of the pipe diameter, therefore the inlet of the truck tire culvert is unsubmerged. Three types of flow have been identified for unsubmerged culverts (*2*). These flow types along with their flow conditions are illustrated in Table 1, where h is the head water depth and other symbols have either been defined previously, or are defined below. To simplify the analysis, the tail-water depth, h_t is assumed to be less than the critical depth, h_c of the flow, so type 1 and type 2 in Table 1 are the only possible flow types. In the case where h_t is greater than the critical depth, special analyses need to be conducted concerning the specific situations.

The hydraulic capacity of a scrap tire culvert can be obtained by limiting the maximum flow depth to 75% of its diameter. To find the maximum flow depth in a scrap tire culvert, the flow type must be defined first. As illustrated in Table 1, the determination of flow types involves the calculations of critical depth, d_c and normal depth, d_n. The critical depth is defined as the depth of water where the specific energy is minimum for a given discharge and cross section, while the normal depth is the depth of flow corresponding to uniform channel flow. The critical depth and normal depth are calculated by using the following process (2).

To calculate the critical depth, a section factor Z_c for critical flow is introduced and defined as:

$$Z_c = A\sqrt{D} \tag{7}$$

where A is the flow area, D is the hydraulic depth and D=A/T where T is the top width. For a circular pipe at critical flow, equation (7) becomes:

$$Z_c = A\sqrt{\frac{A}{T}} = \frac{1}{\sqrt{2}}A^{\frac{3}{2}}[d_c(d-d_c)]^{-\frac{1}{4}} \ . \tag{8}$$

From the condition of minimum specific energy, another expression of critical section factor can be derived:

$$Z_c = \frac{Q}{\sqrt{g/\alpha}} \tag{9}$$

where Q is the flow discharge of the culvert and α is the energy coefficient. For a turbulent flow in a scrap tire culvert, the distribution of the velocity is fairly uniform; therefore, α is assumed to be unity for this analysis.

The functional relationship between the flow area and the depth based on the geometry are tabulated in hydraulic manuals. Equations (8) and (9) can be solved using an iterative method to determine the critical depth, d_c.

Similarly, to calculate the normal depth, a section factor Z_n for uniform flow is introduced and defined as:

$$Z_n = AR^{\frac{2}{3}} \cdot \tag{10}$$

From Manning's formula (equation (4)), Z_n can be expressed as a function of the flow discharge, Q:

$$Z_n = \frac{Qn}{S^{\frac{1}{2}}} \tag{11}$$

where S is the hydraulic gradient of the flow and is equal to the slope of the culvert, S_0, for a uniform flow.

Equations (10) and (11) can be solved by an iterative method to calculate the normal depth, d_n corresponding to the hydraulic radius, R. Once d_c and d_n are determined, the flow type can be defined according to Table 1.

HYDRAULIC CAPACITIES

As illustrated in Table 1, when $d_c > d_n$, it is type 1 flow and the critical section is at the inlet. The critical depth at the inlet is also the maximum depth in the culvert. The discharge capacity can be calculated by setting $d_c \leq 0.75d$.

When $d_c < d_n$, it is type 2 flow, and critical depth is at the outlet and is not the maximum depth in the culvert. The maximum depth at the inlet needs to be computed to determine the discharge capacity. Figure 1 illustrates the flow conditions. Bernoulli's equation and the continuity equation from the inlet to the outlet for this flow are:

$$d_i + z + \frac{V_i^2}{2g} = d_c + \frac{V_c^2}{2g} + h_f \qquad (12)$$

and

$$A_i V_i = A_c V_c \tag{13}$$

where d_i is the depth at the inlet and d_c is the critical depth at the outlet, V_i is the average velocity at the inlet and V_c is the average velocity at the outlet, z is the difference of elevation between the inlet and outlet and $z = S_0L$, and A_i and A_c are flow areas at the inlet and outlet, respectively.

The frictional head loss can be obtained by referring to equation (3) and assuming that the average velocity in the culvert $V = \sqrt{V_i V_c}$:

$$h_f = \frac{fL}{d}\frac{V_i V_c}{2g} \; . \tag{14}$$

Substituting equation (14) and $z=s_0L$ into equation (12) and rearranging equation (12) gives:

$$d_i + \frac{V_i^2}{2g} - \frac{fL}{d}\frac{V_i V_c}{2g} = d_c + \frac{V_c^2}{2g} - S_0 L \; \cdot \tag{15}$$

With all the parameters known, d_i can be solved from equation (15). The hydraulic capacity is then determined by limiting $d_i \leq 0.75d$.

Figure 2 shows the results of discharge capacity analyses described above for truck tire culverts of different lengths and slopes. It can be seen from Figure 2 that when n = 0.05 (sand ballast used in the culvert), for slopes greater than 11%, the limiting discharge of 0.35 m^3/s is independent of the length and slope of the culvert and the flow is inlet controlled. For slopes between 7% and 11%, the flow capacity is independent of the length but increases with increasing slope. For slopes less than 7%, both length and slope affect the flow capacity; increasing pipe length and/or decreasing slope decreases the flow capacity. For $n = 0.075$, the flow becomes inlet controlled and reaches maximum discharge of 0.35 m^3/s when the slope is greater than 30%.

To use Figure 2 for the design of a truck tire culvert, the design discharge must be determined first (7). Given the design discharge on the ordinate and length of the proposed culvert, determine the slope of the culvert on the abscissa. This slope is the minimum slope required for conveying the design discharge. If the slope of the proposed truck tire culvert is equal or greater than the minimum slope, a truck tire culvert can be used. No factor of safety has been applied to the curves shown in Figure 2. This is left up to the designer for specific applications.

EQUIVALENT CONCRETE AND CORRUGATED METAL PIPES

To evaluate the applicability of a truck tire culvert, it is useful to compare its hydraulic capacity with the capacity of conventional pipes such as concrete and corrugated metal. Assuming that these pipes are flowing full whereas the truck tire culvert is flowing at a maximum depth of 75% of its diameter, the equivalent pipe sizes can be obtained through hydraulic calculations. The equivalent pipe size is defined as the minimum pipe diameter that would allow the conventional culvert to conduct the same amount of water as a truck tire culvert of the same length and slope. The hydraulic capacities of truck tire culverts of varying lengths and slopes have been calculated. The equivalent conventional pipe diameters were determined using the flow conditions and equations in Table 2.

Figures 3 and 4 illustrate the computed equivalent concrete pipe sizes and corrugated metal pipe sizes, respectively. For a truck tire culvert of a certain length and slope, the equivalent concrete and corrugated metal pipe sizes can be found from Figures 3 and 4, respectively. For example, a 300 meter-long truck tire culvert with sand ballast (n=0.05) at a slope of 2.5% has a flow capacity equivalent to a 0.29-m concrete pipe as indicated in Figure 3 or a 0.35-m corrugated metal pipe as shown in Figure 4. Figures 3 and 4 also illustrate that when the flow is inlet controlled, the required diameter of all conventional pipes is 0.49-m. Because the diameter of a truck tire culvert is 0.53-m, this implies that the hydraulic efficiency of a scrap tire culvert approaches that of conventional pipes when the flow in the scrap tire culvert is inlet controlled, or when $S \geq 11\%$ for culverts with sand ballast and $S \geq 30\%$ for culverts without sand ballast.

CONCLUSIONS AND RECOMMENDATIONS

To reduce the friction head loss and mitigate buoyancy effects in truck tire culverts, it is recommended that sand ballast be placed in the bottom portion of the tires and the maximum flow depth be limited to less than 75% of the pipe diameter. Furthermore, the roughness coefficient was estimated to be 0.05 and this value is recommended for a truck tire culvert with sand ballast. For a truck tire culvert without sand ballast, a value of 0.075 is suggested for use.

Because of the small pipe diameter and relatively high roughness coefficient, the maximum discharge capacity of truck tire culverts estimated by using traditional culvert hydraulics is only 0.35m^3/s. Compared with conventional pipes such as concrete and corrugated metals, truck tire culverts have a lower hydraulic capacity. The hydraulic efficiency of a truck tire culvert, however, approaches that of conventional pipes when the flow is inlet controlled.

The hydraulic capacities of truck tire culverts estimated in this analysis were based on conservative assumptions and limitations. The verification of Manning's roughness coefficient from laboratory experiments and field tests is necessary for carrying out more accurate hydraulic analyses of scrap tire culverts.

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Table 1 Flow Types of Scrap Tire Culverts

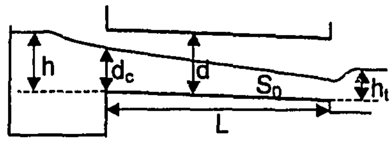
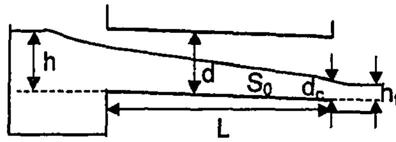
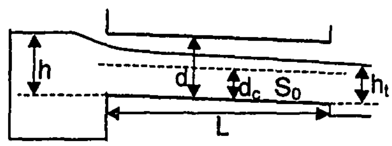
Flow Type	Culvert Slope	Flow Conditions	Control Section	Illustration
1	Steep	$d_c > d_n$ and $d_c > h_t$	Inlet	
2	Mild	$d_c < d_n$ and $d_c > h_t$	Outlet	
3	Mild	$d_c < d_n$ and $d_c < h_t$	Outlet	

Table 2 Flow Conditions and Equations Used for Calculating Equivalent Pipe Sizes

Control Section	Concrete Pipe	Corrugated Metal Pipe	Equation (3)
Inlet	$S_0 \geq 0.01$	$S_0 \geq 0.05$	$Q = C_d A_0 \sqrt{2gh}$
Outlet	$S_0 < 0.01$	$S_0 < 0.05$	$Q = C_d A_0 \sqrt{\dfrac{2g(h+z-d)}{1+29C_d^2 n^2 L / R_0^{4/3}}}$

Note:

1. $n = 0.013$ for concrete pipe and $n = 0.024$ for corrugated metal pipe.

2. C_d is the discharge coefficient and is 0.5 for both concrete pipe and corrugated metal pipe.

3. A_0 and R_0 are the cross section area and hydraulic radius of the pipe, respectively.

4. The tailwater depth is assumed to be less than the pipe diameter.

5. Pipe sizes are obtained at $h=1.5d$.

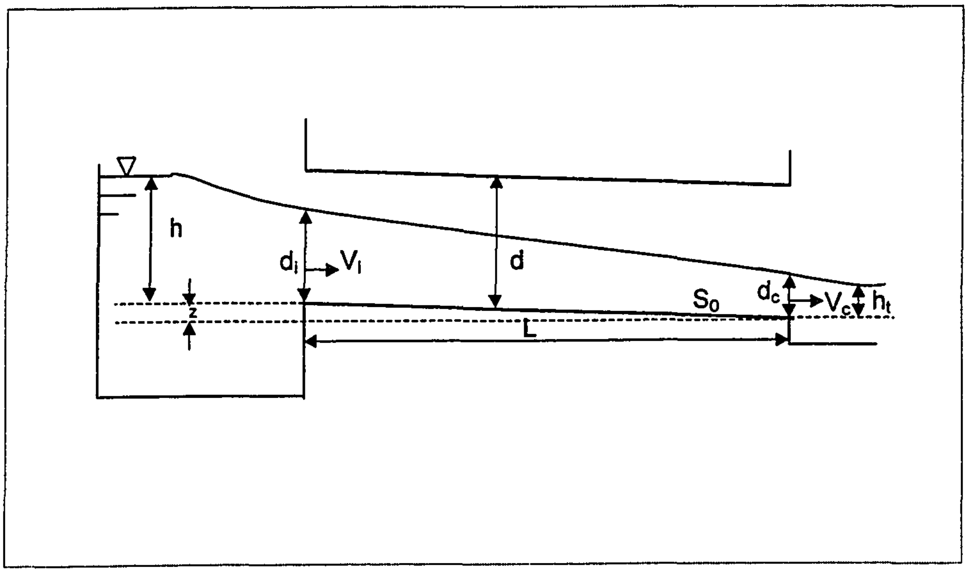


Figure 1 Flow with Outlet Control

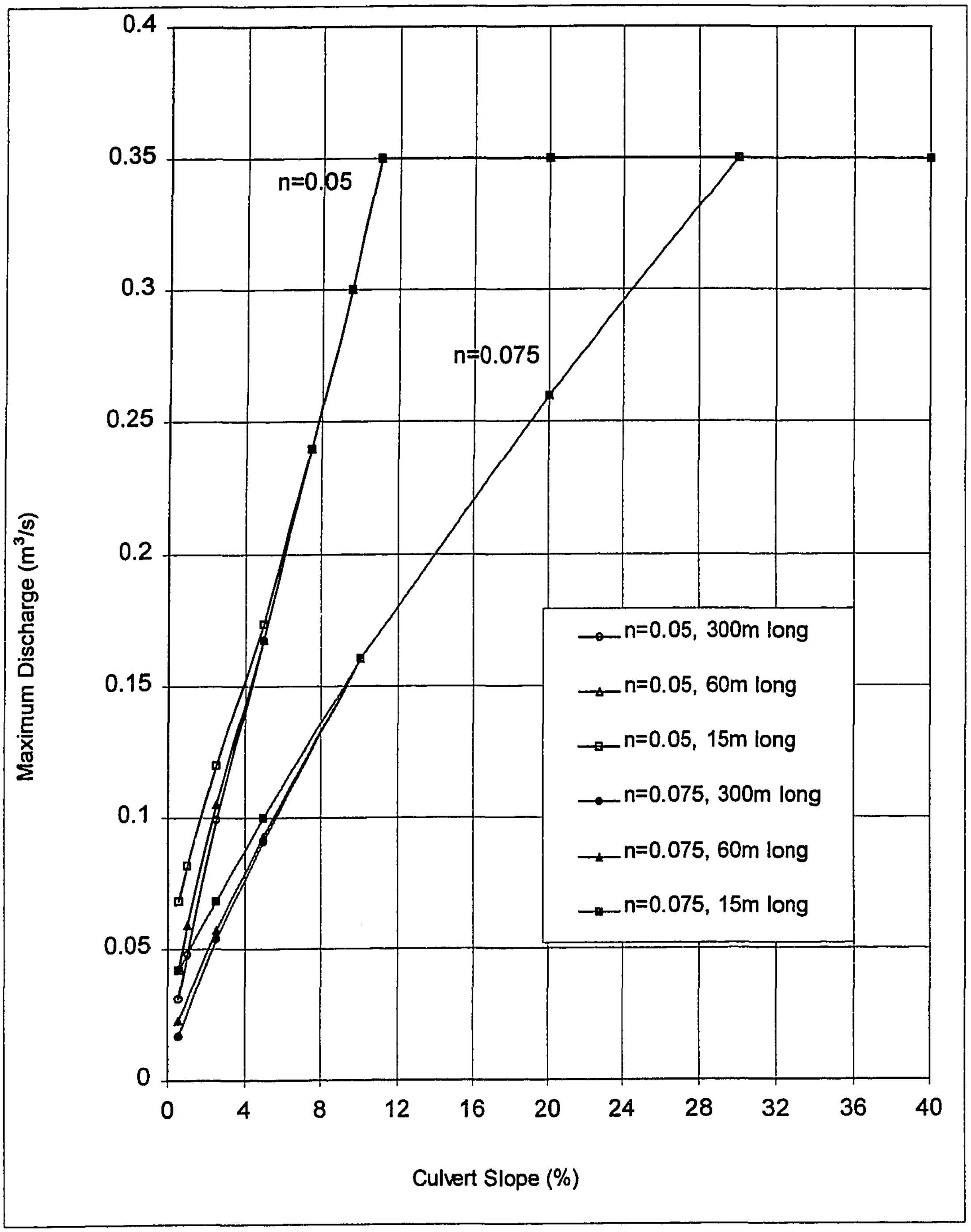


Figure 2 Hydraulic Capacities of Truck Tire Culverts

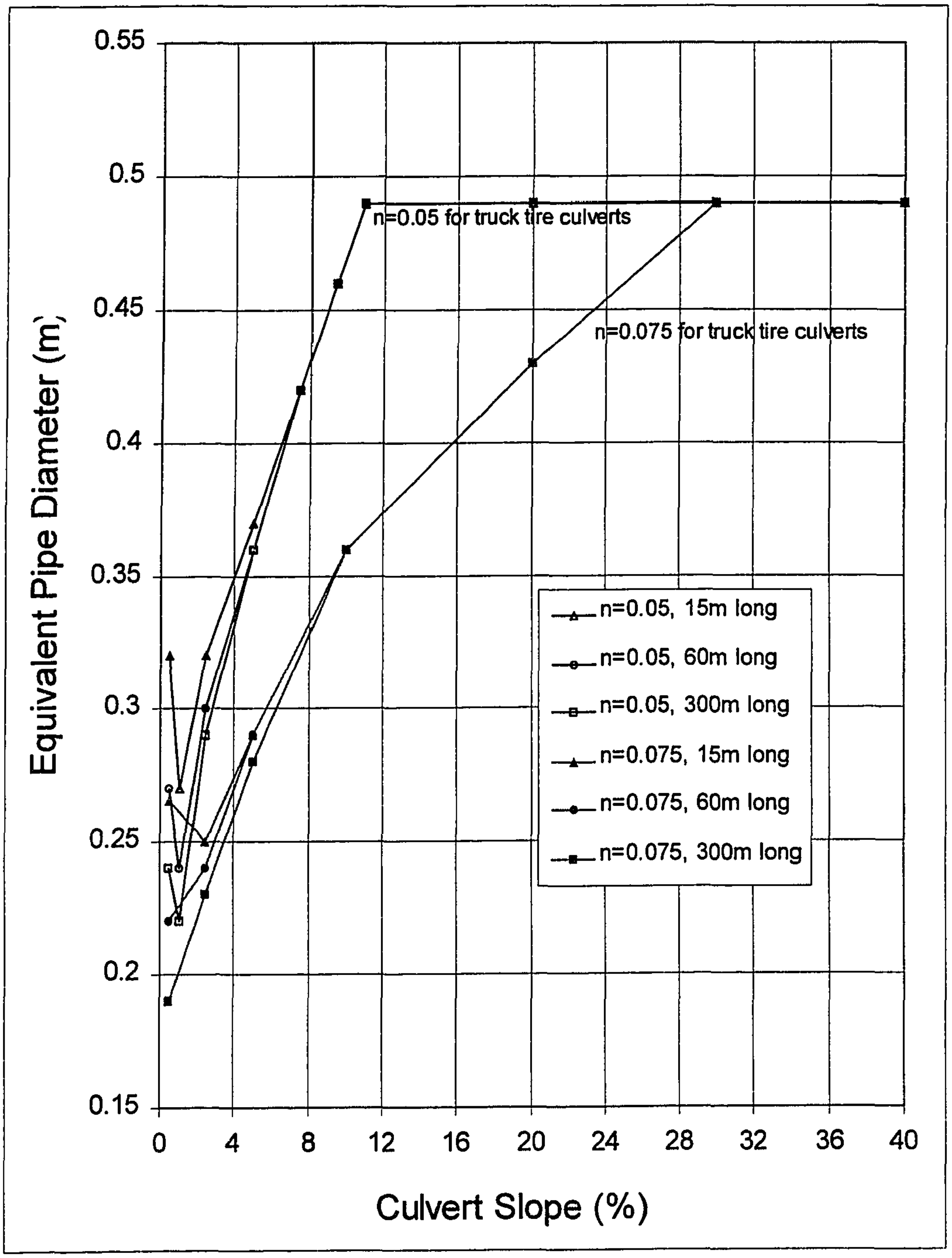


Figure 3 Equivalent Concrete Pipe Sizes

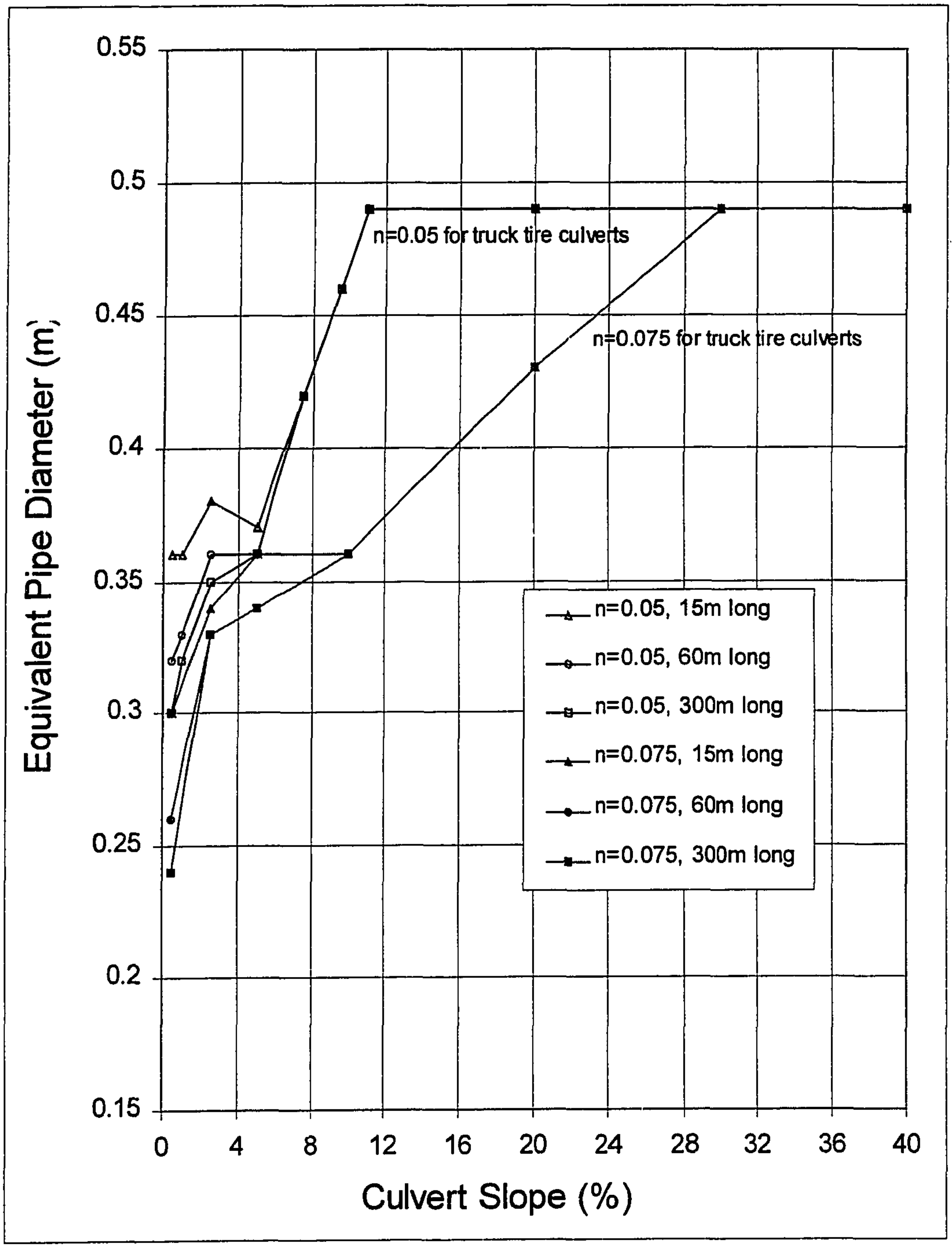


Figure 4 Equivalent Corrugated Metal Pipe Sizes

CHAPTER 3. SCRAP TIRE CULVERTS: STRUCTURAL PERFORMANCE

A paper to be submitted to Canadian Journal of Civil Engineering

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ABSTRACT Culverts constructed of sections of three whole truck tires banded together with steel strapping are a cost effective alternative for draining water from small drainage basins with areas up to several hectares. The design of a truck tire culvert involves both hydraulic and structural performance considerations. This paper focuses on the structural considerations.

Truck tire culvert structural performance depends on the strength and stiffness of the truck tires as well as their interaction with the surrounding backfill soil. The strength and stiffness properties of truck tires were determined by parallel plate testing. Buried conduit field tests were conducted to evaluate the soil-structure interaction under a relatively shallow backfill condition. Responses with well compacted and uncompacted (dumped) glacial till backfill soil were compared. Drawing on the results of the parallel plate tests and using the buried conduit test results for calibration, the Culvert Analysis and Design (CANDE) program was used to assess the load response of a truck tire culvert for a variety of backfill soils and to develop structural performance-based design guidelines.

Keywords: scrap tires, culvert, parallel plate test, field testing, CANDE

INTRODUCTION

It is estimated that about 2 billion scrap tires clutter the US countryside, and that this form of refuse is growing at the rate of about one scrap tire per capita per year (*1, 2*). In an effort to combat this ever growing problem, scrap tires have been cut into chips and reused as tire derived fuel and for civil engineering applications including construction fill materials and drainage layers. While passenger car tires may be readily shredded to produce chips, scrap truck tires are difficult to shred because of the heavy, steel reinforced bead wire. Recognizing this problem, several tire recycling companies have developed innovative truck tire pipe for use as culverts.

Gattis and Everett (*3*) describe truck tire pipe that is formed by stacking, compressing and binding sidewalls cut off of truck tires. In Iowa, a tire recycling company constructed a prototype culvert using whole truck tire pipe (*4*). The only preprocessing required was binding the tires into sections with steel strapping. The prototype culvert performed satisfactorily and was viewed as a cost effective alternative to effectively drain water from small drainage basins with areas up to several hectares. The relevant engineering properties of the whole truck tires and the design and performance aspects need to be quantified, however, to allow use by others.

The design of a truck tire culvert involves both hydraulic and structural performance considerations. This paper focuses on the structural aspects (the hydraulics are reported in *4* and *5*). Truck tire culvert structural performance depends on the strength and stiffness of the truck tires as well as their interaction with the surrounding backfill soil. The strength and stiffness properties of truck tires were determined by parallel plate testing while buried conduit field tests, similar to those reported by Conard et al. (*6*), were conducted to evaluate the soil-structure interaction. Drawing on the results of the parallel plate tests and using the buried conduit test results for calibration, the Culvert Analysis and Design (CANDE) program was used to assess the load response of a truck tire culvert for a variety of backfill soils and to develop structural performance-based design guidelines.

PARALLEL PLATE TESTS

Measurements of truck tires used in this research program indicate that the inside diameter for conducting water ranges from 0.53 m to 0.60 m, with an average of 0.55 m. The outside diameter ranged from 0.99 m to 1.07 m with the most common value being 1.02 m. The widths of the truck tire tread ranges from 0.18 m to 0.24 m with an average value of 0.21 m. Through experience with the prototype culvert and further field testing, it was found that the tires are more stable in a trench and can be installed faster using tire sections; i.e. sections of three tires banded together with steel strapping (*4*).

Parallel plate tests, following the guidance of ASTM D2412 for plastic pipe, were conducted on 37 single tires and nine tire sections to quantify their load-deformation response and to observe failure modes under compression load. The tests were carried out by compressing the tire(s) at a rate of 0.038 m/min to a maximum deflection of 0.254 m. Readings of platen deflection (change in tire outside diameter), change in inside diameter, and applied load were taken every 0.025 m. The tire stiffness (TS) was calculated as TS (kN/m^2) = $F/\Delta Y$ where F = load/total tread width (kN/m) and ΔY is the deflection (change in outside diameter) of the tire (m).

Figure 1a shows a typical parallel plate response of a tire section and the responses of the individual truck tires comprising the section. The change in the inside, water-conducting diameter of the truck tires is only about 10 to15 % of the change in outside diameter. In addition, the load-deformation curve for a tire section is essentially an average response of the three individual tires making up the section. The load-deformation response of tire sections, therefore, are adequately defined by testing single tires. TS values were calculated for the 37 single tires and ranged from 62 to 186 kN/m^2 with an average value of 110 kN/m^2.

Collapse or buckling of tires was observed to occur at outside diameter changes greater than about 0.13 m. An example of this phenomenon is the response of tire 19 in Figure 1a, in which the diameter change continues to increase beyond a value of 0.2 m but with a decrease in load/width. Note, however, that even with collapse of the tire tread section, the inside diameter has changed only by about 0.03 m.

The effect of repetitive loading on truck tire load response was assessed by carrying out six consecutive parallel plate tests on the same three single tires. Each loading cycle comprised compressing the tire to the maximum outside diameter change of 0.254 m at the standard rate noted above, releasing the load and allowing the tire to rebound back to its original shape. The time between the consecutive tests varied from 1 hour to 20 days. The results indicate that the load bearing capability of the truck tires (in terms of load/width) for a given diameter change does not decrease by more than about 5 to 10% over the six consecutive tests. As Figure 1b indicates, the most significant decrease in load/width occurs after the first test, with smaller decreases thereafter. In addition, the time between the consecutive tests did not appear to affect the responses. In practical terms, this indicates that repetitive loading, such as from traffic, should not cause excessive deformation of truck tire culverts.

BURIED CONDUIT TESTS

Test Description

Buried conduit tests were carried out to compare truck tire culvert performance with poorly compacted and well compacted backfill for a shallow trench condition (i.e. about 0.6 m of fill above the top of the tires). Glacial till, classifying as a CL-ML with a maximum standard Proctor dry unit weight of 18.6 kN/m^3 and optimum moisture content of 12 %, was used as the backfill in these tests.

For each test, six tire sections (a total of 18 tires) were placed side-by-side in a trench about 1.8 m wide at the bottom by 1.8 m deep with sides sloping at about 1:1. In keeping the installations simple, no tire section bedding preparations were carried out. String type displacement potentiometers were installed on selected tires to measure outside and inside vertical diameter change.

For Test 1, glacial till backfill was dumped into the excavation without compaction. Figure 2a shows a transverse cross section through the backfilled culvert while Figure 2b shows a longitudinal profile along the culvert length. Two nuclear densometer tests performed at the surface of the fill gave a percent compaction (relative to the standard Proctor maximum) of about 80%. However, previous tests with plastic pipe using the same backfill and placement methods (*7*) showed a variation in relative compaction from about 32% to 61% with an average of about 50%. It is highly likely that a significant portion of the backfill in this first test had a relative compaction closer to about 50% than to the 80% shown by our in situ tests.

For Test 2, glacial till backfill was compacted in three lifts using a tracked-excavator-mounted vibratory plate. Figure 3a shows a transverse cross section through the backfilled culvert while Figure 3b shows a longitudinal profile along the culvert length. The results of six nuclear densometer density tests indicate that the target relative compaction specification (i.e. >95%) was met for all backfill lifts.

Live loads were applied to the surface of the backfill near the midlength and near the end of the culvert (see Figure 2b and 3b) with a hydraulic ram using an overhead frame for reaction. Up to 1388 kN of force could be generated with this system. A steel plate of 0.093-m^2 (i.e. one square foot) area was attached to the hydraulic ram to represent a truck tire. Applied loads were measured using a load cell. For all loading tests, procedures as reported by Conard et al. (*6*) in which the hydraulic ram was extended for a total of 0.34 m of displacement, were used. As noted by Conard et al. (*6*), these test conditions provide a severe, conservative evaluation of the culvert-soil system response. The loading tests were typically completed in about 20 to 30 minutes. Tire outside and inside diameter vertical changes were recorded during both the backfilling and live loading stages.

Test Results

Figure 4a shows the total change in inside and outside tire diameters for the Test 1 backfilling stage. Negative values indicate a decrease in the diameter. Diameter changes were minimal, ranging from about 0.0005 m to 0.005 m. Figure 4b shows the change in inside and outside tire diameter induced by compacting the three backfill lifts in Test 2. Compaction of the backfill beside the tires (lifts 1 and 2) produced net upward deflections (positive diameter changes) ranging from about 0.01 to 0.03 m in most of the tires. The application of lift 3 above the crown of the tires decreased the net upward deflections in most cases.

Figure 5 shows the load versus diameter change response for tires below the loading plate for the Test 1 and 2 load tests near the culvert midlength. The curves indicate relatively small diameter changes until a maximum stress is reached, at which point the stresses decrease and diameter changes increase markedly. This stress-strain response was expected because the hydraulic ram continued to punch into the soil after the peak stress has reached. The total depth the hydraulic ram penetrated into the soil was about 0.2 m. Diameter changes are relative to those induced from backfill soil placement. The maximum stress mobilized and the corresponding tire diameter change, the maximum diameter changes recorded and observations of tire buckling for all six loading tests are summarized in Table 1.

Inspection of Figure 5 and Table 1 shows that significantly higher stresses may be mobilized for well compacted backfills than for loose backfills. Moreover, higher stresses may be mobilized near the midlength of the culvert relative to near the ends for each backfill condition. As the loading plate is punched into the soil backfill with the hydraulic ram, compression of the overlying backfill soil and the contact stresses on the tires will increase. At the maximum stresses mobilized, the plate had typically penetrated into the backfill by about 0.14 to 0.18 m. By elastic stress distribution theory, this condition is more severe than a similarly loaded tire on the backfill surface.

Figure 5 and Table 1 also indicate that maximum diameter changes recorded for inside diameters are typically much smaller than for outside diameters for tests near the midlength of the culvert. For test 1-B and 2-B the maximum inside diameter changes are about 26% and 10%, respectively, of the maximum outside diameter changes recorded for the neighboring tire. These results imply that while the outside diameter may be undergoing relatively large deflections, the inside, water conducting diameter may not be significantly affected.

CANDE ANALYSES

Background And Parameters For Analysis

The structural capacity of truck tire culverts must be sufficient to withstand the geostatic loads of the soil backfill and the superimposed loads from vehicles moving over the soil surface above the culvert. In situations where the culvert is constructed at shallow depths, the live loads from vehicles are greater than the loads resulting from the body force of the soil mass. As the depth of burial increases, the effect of surface loading is attenuated, and stresses imposed by the soil become greater. Elastic theory predicts that if the surface stress is applied over a contact area of about 0.1 m^2, the stress at a depth of 0.3 m will be about 10% of the surface stress. This indicates that the culvert should have a minimum depth of cover to reduce the effect of the surface loads and a maximum depth so that the soil mass will not excessively deform the pipe.

In order to define these limiting depths, CANDE (Culvert ANalysis and DEsign) (*8*) was used to calculate the minimum and maximum soil depths to safely support backfill soil and standard AASHTO H-trucks. Solution level 2, which is a finite element approach with automated mesh generation, and the Duncan-Chang soil constitutive model were used. The parameters needed for CANDE analysis are the pipe diameter and wall thickness, material properties of the pipe including Young's modulus, Poisson's ratio and ultimate stress at rupture, and the properties of backfill and native, in situ soils.

As discussed above, there is a significant difference between the tire outside and inside diameters. Moreover, the sidewall/tread configuration makes the tire cross sectional geometry complex; definition of tire (pipe) wall thickness is not straightforward. To overcome these complexities, a nominal thickness concept in which the tire was assumed to have a simple, rectangular cross section was used. Assuming a tire specific gravity of 1.25 and using representative values of the truck tire weight (471.5 N), width (0.21 m) and outside diameter (1.02 m), a tire thickness of 0.06 m was calculated. The parameters used for the CANDE analayses are summarized in Table 2. Details of the calculation are given in (*4*). Using this tire thickness and the outside diameter of 1.02 m, the average pipe diameter required for CANDE is 0.96 m. With the rectangular cross section assumption, the moment of inertia (I) was calculated as be 1.8×10^{-5} m^3.

Young's modulus (E) was calculated using the parallel plate tire stiffness (TS) values. According to ASTM D2412, the approximate relationship between EI and pipe stiffness, PS, (or TS, in this case) is defined as: $EI = 0.149r^3(TS)$. Substitution of I (1.8×10^{-5} m^3) and r (0.48 m) values and the average TS (110 kN/m^2) gives an E value of 100,000 kN/m^2. The upper and lower bound E values, calculated by using the maximum and minimum values of TS from the parallel plate tests are 170,000 and 56,000 KN/m^2, respectively. A Poisson's ratio of 0.4 was assumed based on tensile tests of a steel-rubber composite (*9*).

No laboratory tests were carried out to measure the ultimate stress at rupture of truck tires, and no data were found in the literature for this value. High-density polyethylene pipe research estimated the ultimate stress at rupture of the pipe material to be 23,400 kN/m^2. It is likely that tires have a lower value of ultimate stress at rupture than polyethylene pipe, so a value of 17,200 kN/m^2 was used.

Silty clay (CL), silty clayey sand (SM-SC) and silty sand (SM) soils were selected as representative backfill soil types for the CANDE analyses used in developing the structural performance design guidelines for truck tire culverts. Three degrees of compaction (45%, 85% and 95% of the maximum AASHTO-T99 dry unit weight) were in turn used for the soils in the analyses. The soil compacted to 45% maximum AASHTO-T99 dry unit weight was to simulate uncontrolled or uncompacted backfill. The Duncan-Chang constitutive law soil parameters for all conditions were obtained from the CANDE data library.

Simulation Of Vehicle Loading

CANDE was originally designed to calculate pipe deflections under geostatic or backfill loads; therefore no modifications were needed to calculate maximum depths of backfill. To simulate truck tire loads in two dimensions and allow calculation of minimum depths of backfill, a method proposed by Katona (*10*) was used. For this method, an equivalent strip load, q, is calculated to represent a single concentrated point load, Q. This approach is based on the soil stress equivalence at the top of the pipe for the concentrated load and the strip load. The equivalent strip load, q, is expressed as:

$$q = \frac{3}{4}\left(\frac{Q}{L}\right) \qquad (1)$$

where L is the shortest distance from the point load to the top of the pipe.

In the CANDE analyses, the actual loads in the field buried conduit tests and simulated H15-truck loads were treated as concentrated loads and converted to equivalent strip loads using equation (1). For analysis of the buried conduit tests, the magnitude of the equivalent strip load was adjusted for the penetration of the loading plate into the backfill by adjusting L in equation (1) accordingly.

CANDE Analysis Of Buried Conduit Tests And Parameter Sensitivity Analysis

A comparison of CANDE calculated deflections with measured deflections for the buried conduit midlength loading tests are shown in Figure 6 and 7. For test 1 (Figure 6), CANDE analyses were carried out for soil parameters corresponding to both 45% compaction and 80% compaction. As expected, the CANDE analysis for the 45% compaction parameters gives larger deflections than the analysis for 80% compaction parameters. The measured deflections tend to agree with the 80% curve earlier in the test, and with the 45% curve as the maximum mobilized stress is approached and the plate penetrates the backfill. This tends to support the hypothesis that the backfill was compacted close to 80% near the surface, with lower unit weights below. The comparison for Test 2 shows greater analytical deflections than measured deflections.

A half order of magnitude difference exists between the upper and lower bound tire stiffness values determined from the parallel plate tests (i.e. from 62 to 186 kN/m^2). The average value of 110 kN/m^2 was used for calculating the tire pipe Young's modulus for the CANDE analyses. The sensitivity of the calculated maximum tire deflection to the tire pipe Young's modulus was examined for a variety of backfill conditions with CL, SM-SC and SM soils (see Figure 8). The CANDE library soil parameters for 85% relative compaction were used for all analyses. As expected, the highest tire pipe Young's modulus gives the lowest deflections for each of the analyses. The most significant difference in maximum deflection between using the upper and lower bound tire pipe Young's modulus values is for the case of 0.61 m of backfill cover and H-15 truck loading applied. Even in these cases, however, the deflections only change by about 0.01 to 0.015 m. Moreover, reducing the tire pipe Young's modulus from the average value to the lower bound value (about a factor of two) increases maximum deflections by about 0.005 to 0.01 m. These sensitivity analyses have shown that the maximum deflections are relatively insensitive to tire pipe Young's modulus. Variations in tire stiffness should, therefore, have minimal impact on truck tire culvert structural perfomance. Additional analyses showed that the CANDE analysis is very insensitive to Poisson's ratio (*4*).

Minimum And Maximum Backfill From CANDE Analyses

In order to determine the minimum and maximum allowable backfill covers, it is necessary to select some limiting vertical truck tire culvert strain. No published data exist on maximum allowable strains for truck tire culverts. Conventionally, 5% deflection was used as the maximum allowable deflection for flexible pipes (*11*). From Figures 6 and 7, truck tires directly under the load buckled at a deflection of about 1.5-1.8 cm, which is less than 2% strain; however, the traditional 5% criterion was used in this analysis because the buckling of some of the tires has very small impact on the hydraulic capacity of a truck tire culvert. This has been indicated earlier from the field conduit tests (Figure 5) that the change of the inside diameter is only a fraction of the change of the outside diameter after a tire buckles. In addition, the following reasons are also considered.

1 As mentioned earlier, the field conduit tests shown in Figures 6 and 7 were conducted under very severe displacement-controlled condition.

2 The CANDE program tends to overestimate the deflections of a truck tire culvert by at least twice as much as measured in the field (*4*) except a loose backfill test.

3 There was evidence that the Young's modulus and moment of inertia used in this analysis were underestimated (*12*).

4 The sidewalls of the tires provide reinforcement to the ring and increase the tire pipe stiffness (*12*).

5 The parallel plate test data from this study indicate that truck tires buckle or completely fail at deflections after 13% of the pipe outside diameter.

Based on these facts, for design purposes, the maximum allowable strain of the top of tires under backfill soil and surface loading was selected as 5% of the outside tire diameter. This is a limiting deflection of 0.05 m.

With the constraint of pipe deflection less than 5% of the outside diameter, the minimum and maximum soil covers for the soils and degrees of compaction were obtained using the CANDE program. The results of these calculations are in Table 3. The minimum soil covers listed in Table 3 were estimated under both soil load and H15-truck load. The maximum soil covers listed in Table 3 were estimated under geostatic load only because the effect of surface load for deep trenches is negligible.

CONCLUSIONS

Culverts constructed of sections of three whole truck tires banded together with steel strapping are a cost effective alternative for draining water from small drainage basins with areas up to several hectares. Although the design of a truck tire culvert involves hydraulic and structural performance considerations, this paper focuses on the structural considerations. To this end, parallel plate tests, buried conduit field tests and CANDE analyses were carried out to develop structural design guidelines for truck tire culverts.

Parallel plate tests, following the guidance of ASTM D2412 for plastic pipe, gave tire (pipe) stiffness values that ranged from 62 to 186 kN/m^2 with an average value of 110 kN/m^2. Collapse or buckling of tires was observed to occur at outside diameter changes greater than about 0.13 m (about 13% deflection based on an initial outside diameter of 1.02 m). The change in the inside, water-conducting diameter (about 0.53 m initially) is only about 10 to15% of the change in outside diameter. Repetitive parallel plate load tests indicate that the load bearing capability of the truck tires is not significantly affected by six cycles of loading and unloading. This indicates that repetitive loading, such as from traffic, should not cause excessive deformation of truck tire culverts.

Buried conduit field tests were carried out to compare truck tire culvert performance with poorly compacted and well compacted glacial till backfill for a shallow trench condition (i.e. about 0.6 m of fill above the top of the tires). The results show that significantly higher maximum plate stresses may be mobilized with well compacted versus uncompacted, dumped backfill and that lower maximum mobilized stresses generally occur at the ends of the culvert relative to the midlength. In addition, tests near the midlength of the culvert indicate that maximum diameter changes recorded for inside diameters are typically much smaller than for outside diameters. These results imply that while the outside diameter may be undergoing relatively large deflections, the inside, water conducting diameter may not be significantly affected.

The Culvert Analysis and Design (CANDE) program was used to develop structural design guidelines. Comparison of CANDE analyses with buried conduit live load tests indicate that the CANDE analyses are conservative and tend to slightly overpredict tire deflections for a given load. Sensitivity analyses indicate that maximum deflections calculated using CANDE were relatively insensitive to variations in tire Young's modulus.

Minimum and maximum allowable backfill covers were determined with CANDE using a maximum allowable strain of the top of tires under backfill soil and surface loading of 5% of the outside tire diameter. The minimum soil covers were estimated under both soil load and H15-truck load. The maximum soil covers were estimated under geostatic load only because the effect of surface load for deep trenches is negligible.

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Table 1 Buried Conduit Test Results

Buried Conduit Test	Tire #	Maximum Stress (kN/m^2)	Diameter Change at Maximum Stress (m)	Deflection at Maximum Stress (%)	Maximum Diameter Change (m)	Deflection at Maximum Diameter Change (%)	Buckling
1-A	3 inside	67.2	0.00536	-	0.00536	-	No
	4 outside	67.2	0.00610	0.60	0.00610	0.60	No
1-B	9 inside	130.0	0.00476	-	0.0278	-	Yes
	10 outside	130.0	0.0188	1.84	0.1051	10.3	Yes
1-C	15 inside	61.2	0.00191	-	0.00261	-	No
	18 inside	61.2	0.00376	-	0.0136	-	Yes
2-A	6 inside	326.9	0.00183	-	0.00660	-	Yes
	1 outside	326.9	0.00764	0.75	0.0136	1.33	Yes
2-B	9 inside	538.3	0.00010	-	0.0184	-	Yes
	4 outside	538.3	0.0134	1.31	0.1823	17.9	Yes
2-C	10 outside	571.4	0.0114	1.12	0.102	10.0	Yes
	7 outside	571.4	0.0159	1.56	0.150	14.7	Yes

Table 2 Pipe Parameters Used in CANDE Analysis

Average Diameter (m)	Average Thickness (m)	Moment of Inertia ($10^{-5}m^3$)	Poisson's Ratio	Young's Modulus (kN/m^2)	Ultimate stress at rupture (kN/m^2)
0.96	0.06	1.8	0.4	100,000	17,200

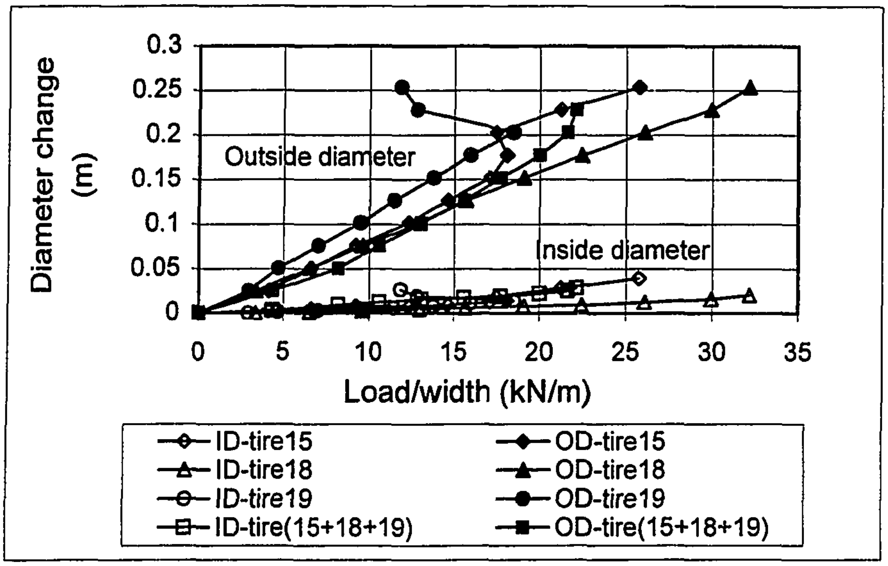
Table 3 Recommended Minimum and Maximum Soil Covers

a). Recommended minimum soil covers under H15-truck load (m)

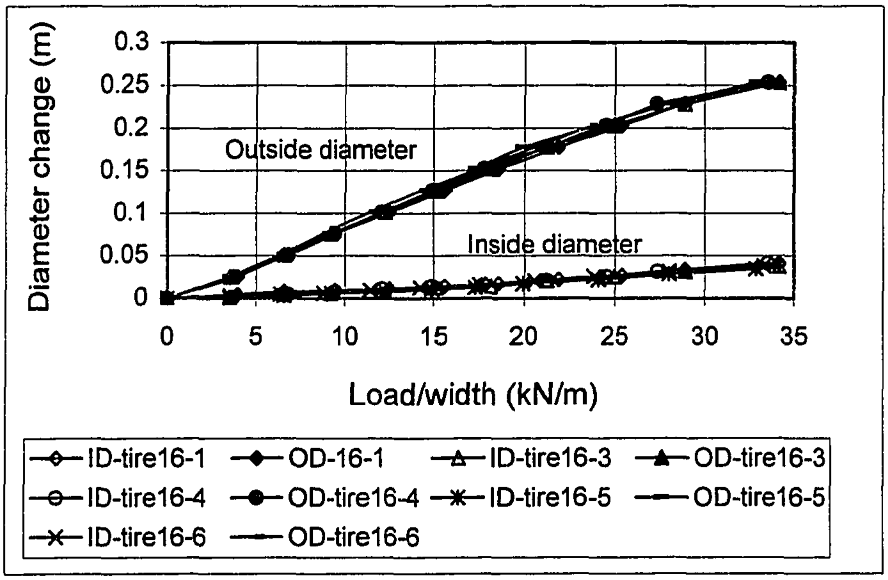
Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	1.2	0.6	0.6	0.6	0.5	0.5	0.3
Sides are poorly compacted (45%)	1.2	1.2	0.9	0.9	0.9	0.9	0.9

b). Recommended maximum soil covers under geostatic load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	13	19	18.5	22	26	41.5	47.5
Sides are poorly compacted (45%)	13	4.5	5.5	6	7.5	10.5	16

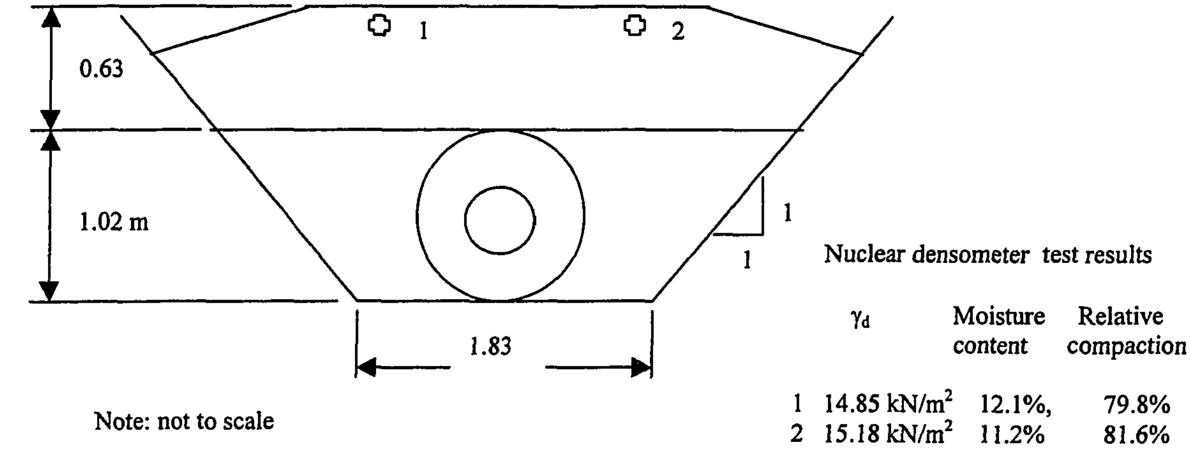


a). Outside diameter (OD) and inside diameter (ID) response of individual tires versus tire section.

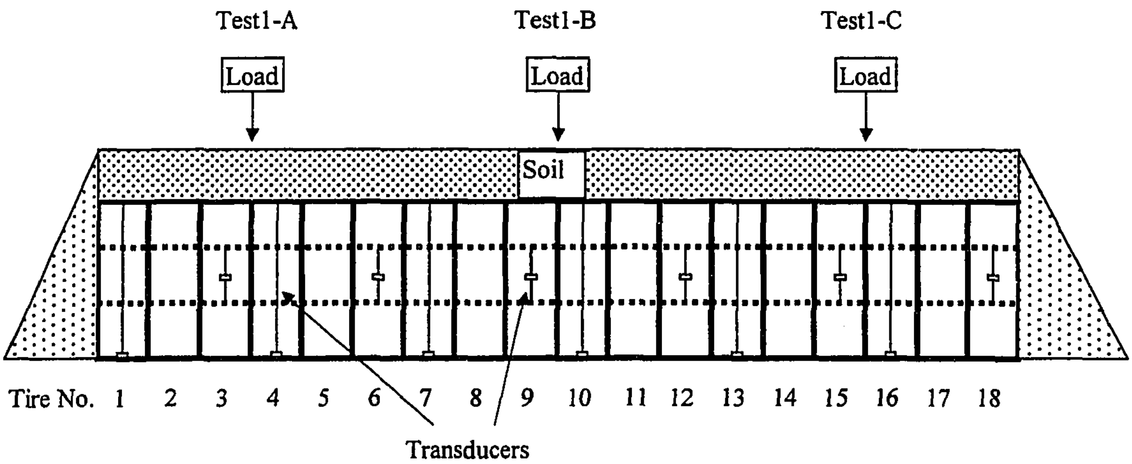


b). Repetitive tests on tire 16.

Figure 1 Parallel Plate Tests

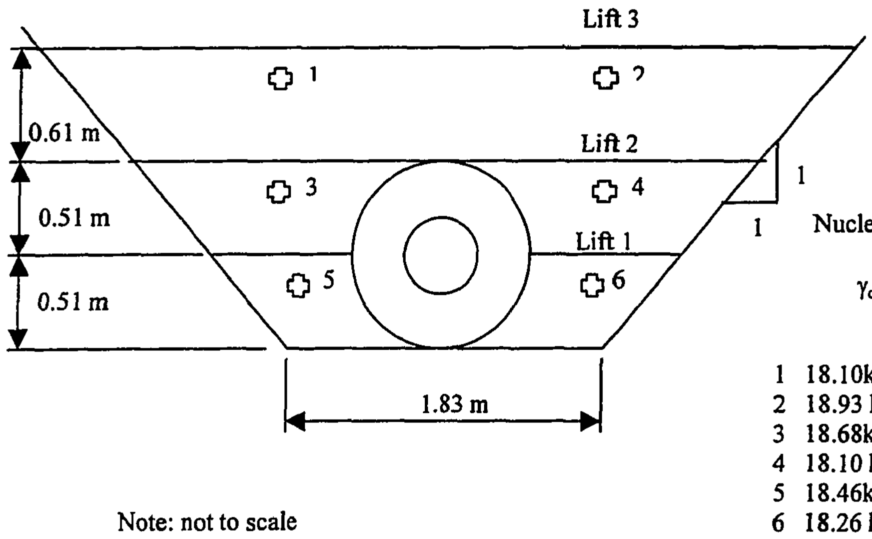


a). Transverse Cross Section



b). Longitudinal Section Showing Tire and Transducer Arrangement and Loading Positions

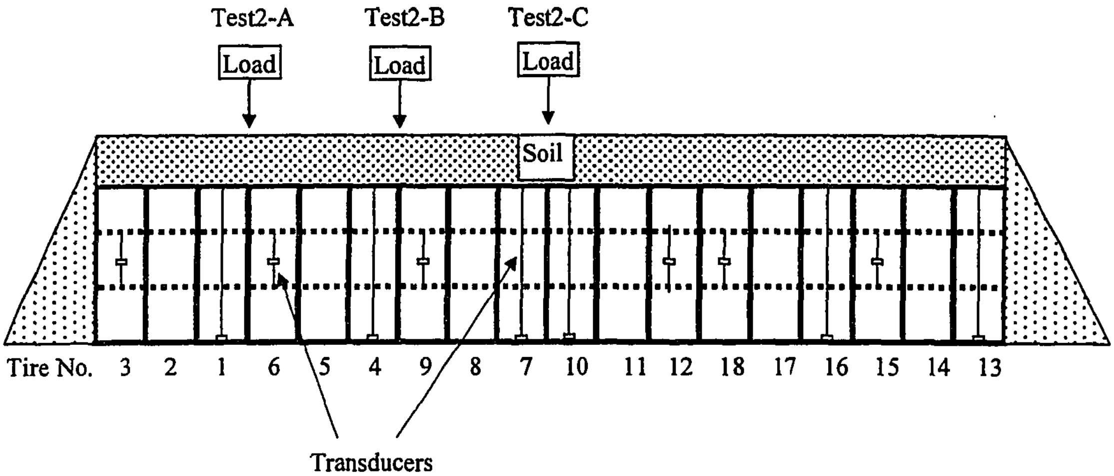
Figure 2 Buried Conduit Test 1 Setup



Nuclear densometer test results

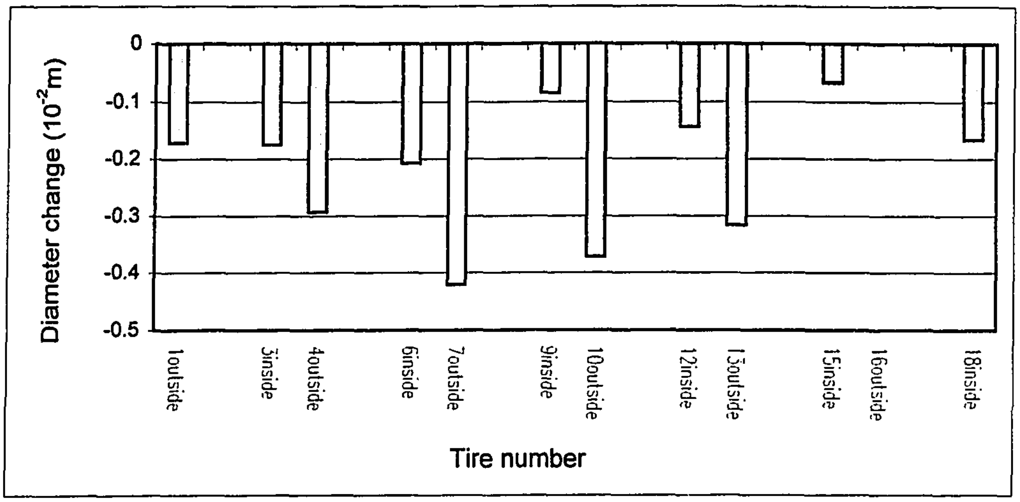
	γ_d	Moisture content	Relative compaction
1	18.10kN/m^2	15.7%	97.4%
2	18.93 kN/m^2	12.5%	102%
3	18.68kN/m^2	10.7%	101%
4	18.10 kN/m^2	11.6%	97.4%
5	18.46kN/m^2	12.2%	98.8%
6	18.26 kN/m^2	10.7%	97.8%

a). Transverse Cross Section

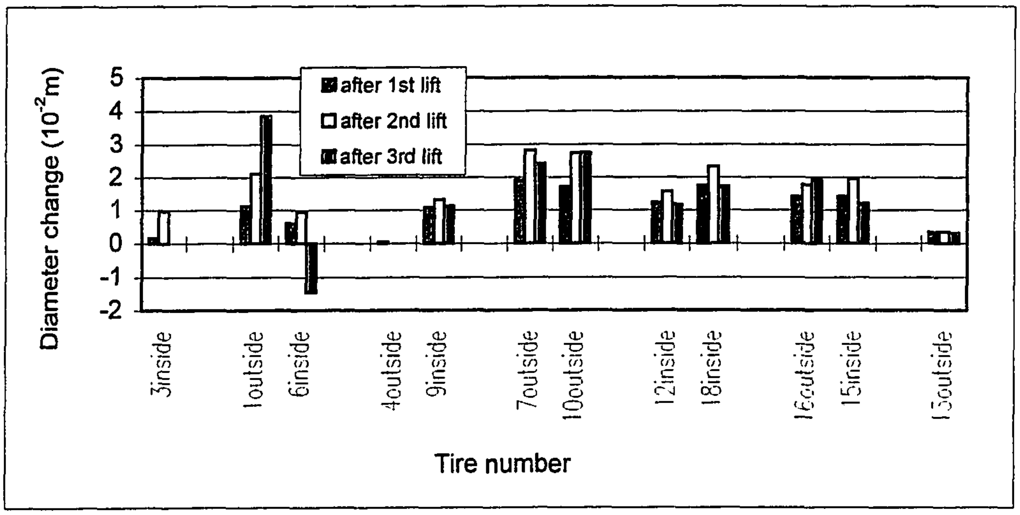


b). Longitudinal Section Showing Tire and Transducer Arrangement and Loading Positions

Figure 3 Buried Conduit Test 2 Setup



a). Buried conduit test 1



b). Buried conduit test 2

Figure 4 Total Change in Tire Diameters Due To Backfilling

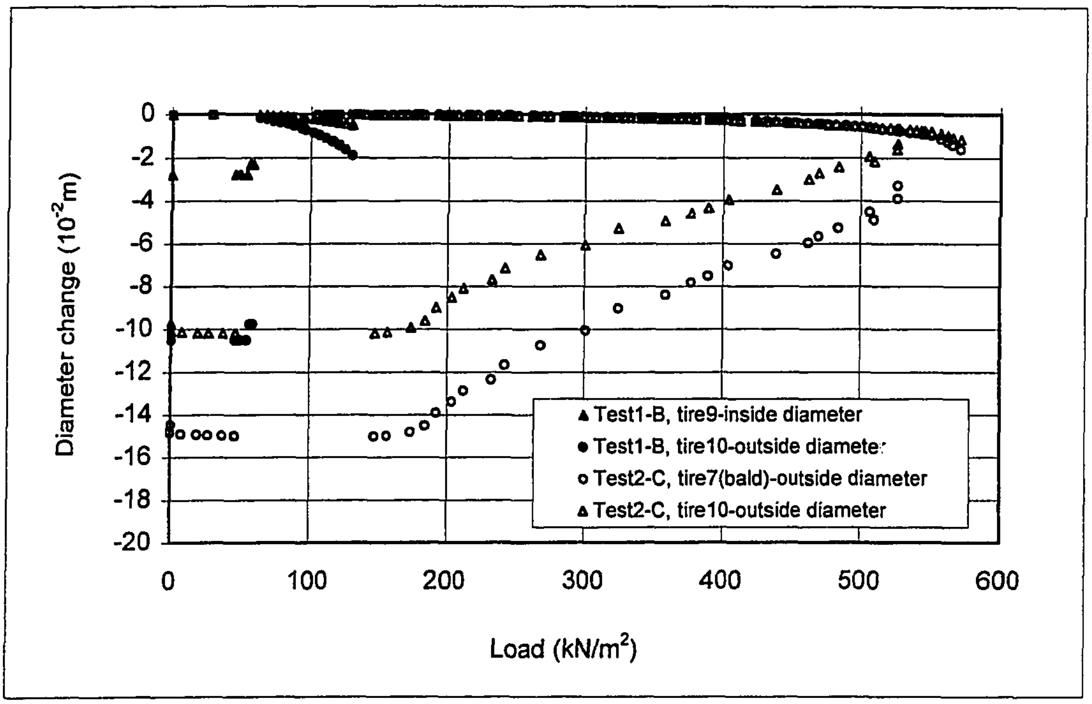


Figure 5 Applied Load Versus Tire Diameter Change For Buried Conduit Load Test 1-B and Test 2-c

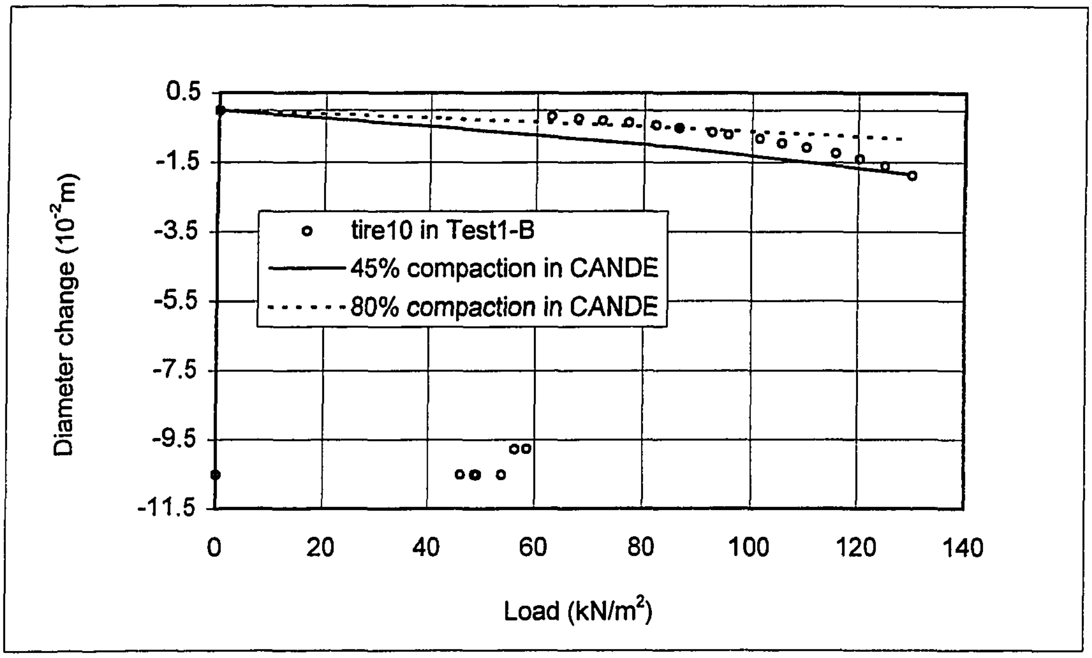


Figure 6 Comparison of Buried Conduit Test 1-B Measured Deflections with CANDE Caculated Deflections

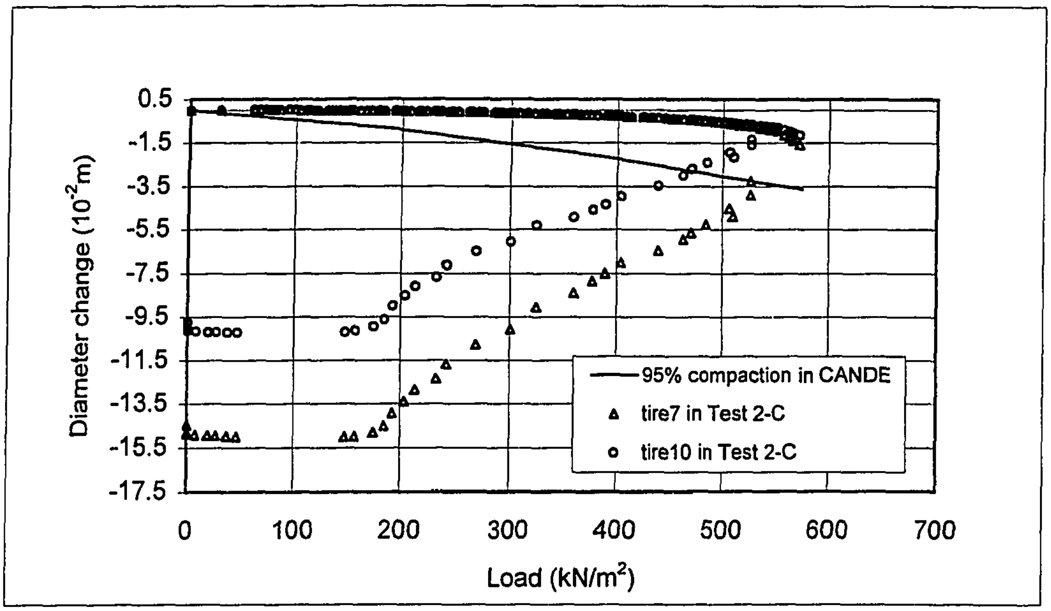


Figure 7 Comparison of Buried Conduit Test 2-C Measured Deflections with CANDE Calculated Deflections

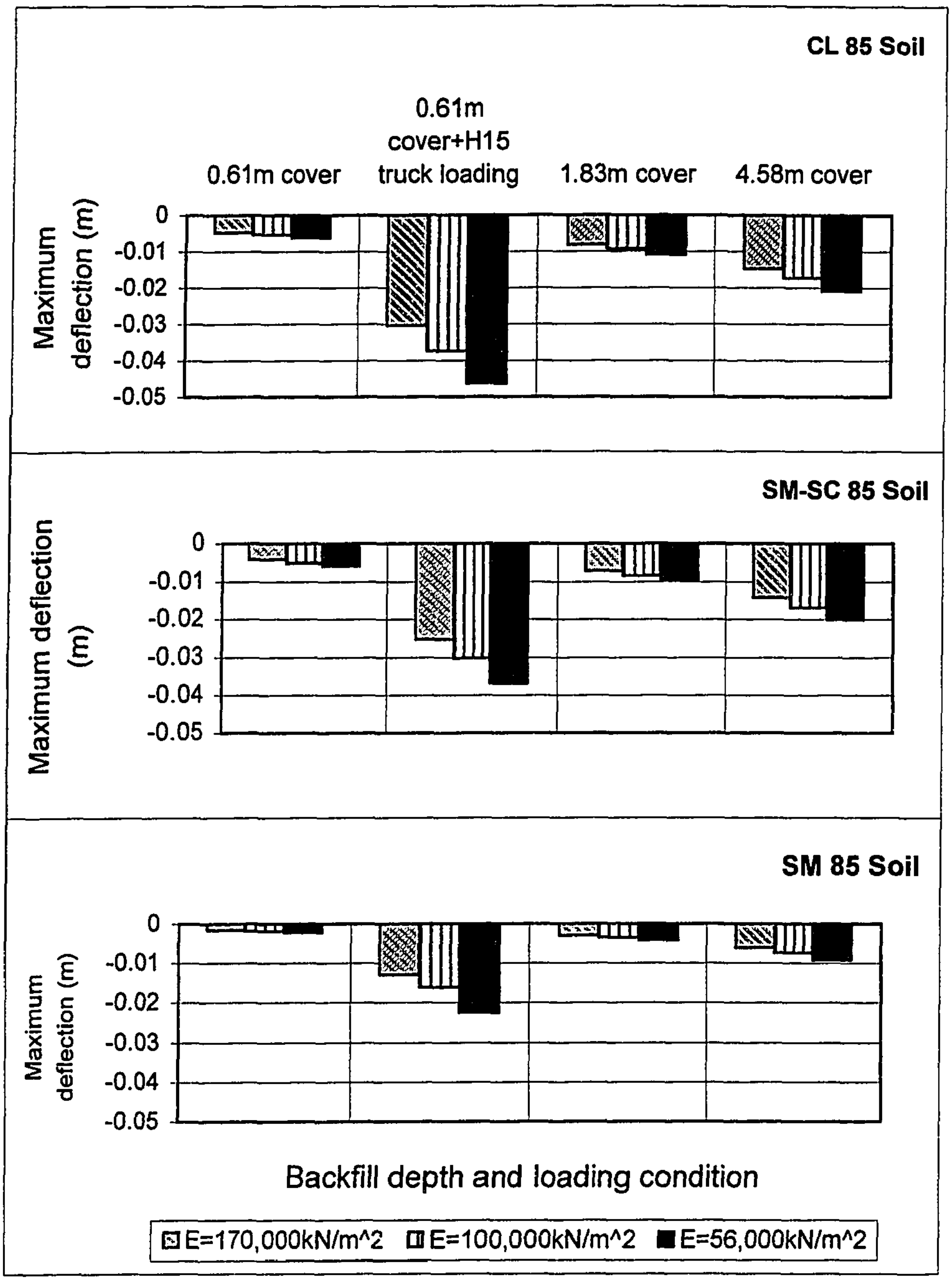


Figure 8 CANDE Sensitivity Analysis

CHAPTER 4. LABORATORY DETERMINATION OF YOUNG'S MODULUS FOR LOW-STIFFNESS FLEXIBLE PIPES

A paper prepared for the ASTM Geotechnical Testing Journal

Shiping Yang, Rebecca L. S. Kellogg, Bruce H. Kjartanson, and Robert A. Lohnes

ABSTRACT The traditional equation for determining the flexural Young's modulus is not appropriate for very flexible pipes due to their high compressibility. A new equation governing the load and deflection relationship of low-stiffness flexible pipes under parallel plate testing is derived. This equation is applied to whole scrap tires used for constructing underground culverts, and the pipe stiffness factor is calculated. In order to obtain the Young's modulus of a scrap tire culvert, the moment of inertia of the cross section of a tire must be determined. Due to the irregular cross sectional area of scrap tires, the calculation of the moment of inertia is difficult. A method is proposed here to estimate the moment of inertia through measurement of physical properties of a scrap tire. The flexural Young's modulus of a scrap truck tire is then determined from the new equation. The estimated parameters were used in the Culvert Analysis and Design (CANDE) program to analyze field buried conduit tests. The results using the flexural Young's modulus from the new equation compared more favorably with the field testing data than those calculated from the traditional equation. Although the new equation was derived for a scrap tire culvert, it is applicable to any low-stiffness pipe.

Keywords: Flexible pipes, pipe stiffness, moment of inertia, Young's modulus

BACKGROUND

To evaluate the load-deflection response of a buried pipe, the stiffness of the pipe must first be determined. As described in ASTM D-2412, the stiffness factor, SF, of a plastic pipe can be measured through parallel plate testing:

$$SF = EI = 0.149 r_0^3 (PS) \qquad (1)$$

where E is the flexural Young's modulus of the pipe, I is the moment of inertia of the cross section of the pipe, r_0 is the mean radius of the pipe, and PS is the pipe stiffness and is defined as:

$$PS = \frac{P}{\Delta} \qquad (2)$$

where P is the load applied to the pipe divided by the length of the pipe section under the load and Δ is the corresponding pipe deflection.

Equation (1), which is referred to as the traditional equation in this paper, was derived by applying elastic theory to a closed thin ring. It was assumed that the radius of curvature of the loaded ring is nearly equal to the radius of the unloaded ring, i.e., the deflection is very small. For rigid pipes, this assumption is reasonable and equation (1) can be applied directly.

For flexible pipes of relatively large pipe stiffness, Equation (1) may also be used as an approximation (Spangler, 1941); however, for very flexible pipes with pipe stiffness values as low as 35kPa (5psi), the traditional equation is no longer valid. The low-stiffness flexible pipes do not maintain circular or elliptical shape under compression. Moore (1994) has indicated that equation (1) is inappropriate for high density polyethylene (HDPE) pipes because of time-dependent, viscoelastic effects, the profiled surface of the pipe, and the nonlinearity of the deformation during parallel plate loading. Moore and Zhang (1998) also suggested that the nonlinearity of the stress-strain response of the HDPE pipe is significant because their linear viscoelastic finite element model overestimated the vertical load (or underestimated the deflection) with increasing errors as pipe deflections exceeded 5%. Based on these issues, it is important to investigate the nonlinear relationship between load and deflection for very flexible pipes as the use of low-stiffness flexible pipes has increased dramatically (Jeyapalan, et al., 1987; Prevost and Kienow, 1994).

A new equation governing the load and deflection relationship for very flexible pipes is derived, and it is applied to scrap tires that are used to construct underground culverts as a low cost alternative to traditional culverts, such as plastic and concrete pipes. The stiffness factor of a scrap tire culvert, which is a product of the Young's modulus and the moment of inertia as shown in equation (1), is estimated with the new equation. However, to evaluate the structural performance of a scrap tire culvert using finite element computer programs, both Young's modulus and moment of inertia must be determined separately.

DERIVATION OF THE NEW GOVERNING EQUATION FOR LOW-STIFFNESS PIPES

Observations of very flexible pipe under parallel plate loading reveal that the configuration of the pipe after compression is neither circular nor elliptical. The section under the platens forms a rectangle and the section outside the plates is two semi-circles as is illustrated in Figure 1. Assuming the load is distributed uniformly under the rigid plate and the length of the neutral axis does not change after loading, a new function governing the load and deflection of the pipe can be derived as follows.

From the second assumption made above, we have

$$2\pi r_0 = 4L + 2\pi r \cdot \qquad (3)$$

It is clear from Figure 1 that

$$\Delta = 2r_0 - 2r \cdot \qquad (4)$$

From equations (3) and (4), we have

$$L = \frac{\pi}{4}\Delta \qquad (5)$$

and

$$r = r_0 - \frac{\Delta}{2} \quad . \qquad (6)$$

Because the pipe and the load are symmetric both horizontally and vertically under parallel plate loading, only the free body of the upper left-hand quadrant of the hoop, i.e., OAB in the coordinate system shown in Figure 2, needs to be considered.

It is evident that there is no shear stress at O and B, and the thrust at O must be equal to half of the total load P, which is defined as F. Assuming the moment at point O is M_0 and considering the equilibrium of moments at point O, the moment at any section between O and A can be expressed as:

$$M = Fx - M_0 = Fr(1 - \cos\theta) - M_0 \qquad (7)$$

and the moment at any section between A and B can be expressed as

$$M = Fx - \frac{F}{2L}(x - r)^2 - M_0 \quad . \qquad (8)$$

The total change in angle between tangent lines at O and B before and after the loading is 0, so:

$$\frac{1}{EI}\int_{O}^{B} M ds = 0 \quad \text{or} \quad \int_{O}^{B} M ds = 0 \cdot \qquad (9) \quad \text{(Church, 1916)}$$

By substituting equations (7) and (8), equation (9) becomes:

$$\int_{O}^{A}(Fr(1-\cos\theta)-M_0)rd\theta + \int_{A}^{B}(Fx-\frac{F}{2L}(x-r)^2-M_0)dx = 0 \cdot \qquad (10)$$

The moment at O after deformation can be found by solving equation (10):

$$M_0 = \frac{(\frac{\pi}{2}-1)Fr^2 + FrL + \frac{1}{3}FL^2}{\frac{\pi}{2}r+L} \cdot \qquad (11)$$

The relative vertical displacement between O and B is $\Delta/2$ and

$$\frac{\Delta}{2} = \frac{1}{EI}\int_{O}^{B} Mxds \cdot \qquad (12) \qquad \text{(Church, 1916)}$$

By substituting equations (7) and (8), equation (12) becomes:

$$\frac{\Delta}{2} = \frac{1}{EI}\{\int_{O}^{A}(Fr(1-\cos\theta)-M_0)r(1-\cos\theta)rd\theta + \int_{A}^{B}(Fx-\frac{F}{2L}(x-r)^2-M_0)xdx\} \cdot \qquad (13)$$

Substituting M_0 from equation (11) and integrating equation (13), Δ can be expressed as:

$$\Delta=\frac{2F}{EI}\{(\frac{3\pi}{4}-2)r^3-[\frac{(\frac{\pi}{2}-1)r^2+rL+\frac{1}{3}L^2}{\frac{\pi}{2}r+L}][(\frac{\pi}{2}-1)r^2+rL+\frac{1}{2}L^2]-\frac{1}{4}r^2(2r+L)$$
$$+\frac{1}{3}(1+\frac{r}{L})[(r+L)^3-r^3]-\frac{1}{8L}[(r+L)^4-r^4]\} \qquad (14)$$

For convenience, let

$$cr_0^3=(\frac{3\pi}{4}-2)r^3-[\frac{(\frac{\pi}{2}-1)r^2+rL+\frac{1}{3}L^2}{\frac{\pi}{2}r+L}][(\frac{\pi}{2}-1)r^2+rL+\frac{1}{2}L^2]-\frac{1}{4}r^2(2r+L)$$
$$+\frac{1}{3}(1+\frac{r}{L})[(r+L)^3-r^3]-\frac{1}{8L}[(r+L)^4-r^4] \qquad (15)$$

Note that r and L in equation (15) are functions of the ring deflection, Δ, and the pipe radius, r_0, as indicated in equations (5) and (6). Since Δ can always be expressed as a percentage of r_0, the RHS of equation (15) can be simplified to a coefficient times r_0^3 at a specific Δ. Therefore it is more convenient to let the RHS of equation (15) equal a coefficient, c, multiplied by r_0^3.

Therefore, equation (14) becomes:

$$\Delta = cr_0^3 \frac{P}{EI} \cdot \qquad (16)$$

Figure 3 shows the relationship of c and δ, where δ here is the percentage of the deflection of the average diameter d_0, as is customary. The coefficient c is 0.149 when δ=0, and thus the traditional equation still holds at very small deflections. As the deflection increases, c increases and reaches a maximum value of 0.201 at a deflection of 53%. After that, c decreases as deflection increases. A polynomial function is shown in Figure 3. This function is for the range of δ from 0 to 100%. This range is not necessary for most practical problems, as design guides often require ductile response to only 20% vertical deformation (Moore and Zhang, 1998). The values of c and M_0 at deflections from 0 to 20% are calculated and presented in Table 1. A simple linear regression between c and δ obtained with sufficient accuracy for δ from 0 to 20% is shown in Figure 4. The linear function is:

$$c = 0.150 + 0.0016\delta(\%) \cdot \qquad (17)$$

From equations (2) and (16), the pipe stiffness can be expressed as:

$$PS = \frac{EI}{cr_0^3} \cdot \qquad (18)$$

So,

$$\Delta = \frac{(0.150 + 0.0016\delta(\%))Pr_0^3}{EI} \text{ or } EI = (0.150 + 0.0016\delta(\%))r_0^3 \frac{P}{\Delta} \quad . \qquad (19)$$

Comparing equation (19) with the traditional equation (1), three important conclusions are drawn in terms of very flexible pipes: 1) the load versus deflection is nonlinear (The increase of c can be viewed as a decrease of E as δ increases in equation (19)); 2) the traditional equation overestimates the loads (or underestimates the deflections) as confirmed by Moore and Zhang (1998); 3) the traditional equation underestimates the EI value. The error is about 6% at 5% deflection, which is not very significant. But the error increases as the deflection increases and becomes significant at high deflections. For example, at 20% deflection the error is about 22%.

DETERMINATION OF MOMENT OF INERTIA OF A SCRAP TIRE

Generally, the moment of inertia is determined from the cross sectional shape of the pipe wall. For a rectangular shape, the moment of inertia per unit length of the pipe, I, is calculated by:

$$I = \frac{t^3}{12} \qquad (20)$$

where t is the thickness of the pipe wall.

Due to the irregular cross section of a scrap tire, equation (20) cannot be applied to scrap tires directly. A methodology is developed here to estimate the moment of inertia of a scrap tire and a concept of nominal thickness is introduced. This concept is based on the assumption that the cross section of the tires is rectangular and the weight, width and outside diameter of the tire are the measured values. Figure 5 is an illustration of how the nominal tire thickness was determined. The specific gravity of tires was determined previously to be 1.10-1.36 with an average of 1.22 (Edil et al., 1994 and Zimmerman, 1997). Since truck tires contain more steel, the specific gravity for truck tires was estimated to be 1.25. The unit weight of the tire, then, is: $9.81 \times 1.25 = 12.3$ (kN/m^3). Based on the measurements of a representative truck tire (a tire that has the size of the average of 33 tires), the following values were obtained:

Weight = 471.4 N;

Tread width = 0.21 m;

Outside diameter OD = 1.02 m.

Thus the transverse cross sectional area of the tire is:

$$A = \frac{471.5/12.3}{0.21} = 0.18 m^2 \cdot$$

The transverse cross sectional area can also be expressed as:

$$A = \frac{\pi}{4}(OD^2 - ID^2) \qquad (21)$$

where ID is the equivalent inside diameter. Solving for ID gives a value of 0.90m.

The mean diameter, d_0, and the mean radius, r_0,of the tire are then 0.96m and 0.48m, respectively, and the nominal thickness, t, is (1.02-0.90)/2=0.06m. The moment of inertia of a truck tire is then calculated using equation (20):

$I = 0.06^3/12 = 1.8 \times 10^{-5}\ m^3$.

From the definition of the moment of inertia, the method proposed here gives a lower value than the true value of a truck tire, and therefore is conservative.

DETERMINATION OF THE FLEXURAL YOUNG'S MODULUS OF A TRUCK TIRE CULVERT

In the application of a scrap tire culvert, equation (19) can be written as:

$$EI = (0.150 + 0.0016\delta(\%))r_0^3(TS) \qquad (22)$$

where TS is the tire stiffness and is defined as the same as the pipe stiffness in equation (2), i.e., $TS=P/\Delta$.

Since the moment of inertia, I, has been determined and TS can be readily calculated from parallel plate test data, the Young's modulus E can be obtained from equation (22).

Equation (22) suggests that TS should always decrease as the deflection increases since EI is a constant. However, Figure 6, which shows the characteristics of TS versus Δ of truck tires under parallel plate testing, indicates that TS decreases at deflections up to 15% and increases slightly at greater deflections. This is due to the irregular cross sectional shape of a tire. As the compression continues, the sidewalls of the tire have more and more effect on the tire stiffness. After about 15% deformation (15cm), the sidewalls bulge out noticeably and provide reinforcement to the ring. Therefore the tire stiffness is increased. In order to get the true value of E for scrap tires, only the TS at 5%, 10% and 15% deflections were used for calculation. Table 2 lists the average values of TS and EI calculated from equation (22) for 33 truck tires. The trend of decreasing TS and relatively consistent EI can be observed.

Using the average of EI at 5%, 10% and 15% deflections and I of 1.8×10^{-5} m^3, the average Young's modulus of the truck tires is calculated to be 120,000 kN/m^2. This value is 20% larger than the E calculated from the traditional equation.

COMPARISON OF CANDE ANALYSIS AND THE EXPERIMENTAL DATA

The estimated values of E and I were used in the CANDE (Culvert ANalysis and DEsign) finite element program to compare the analytical solution with the experimental data from a buried conduit test. Other parameters such as Poisson's ratio and ultimate stress at rupture used in this analysis were the same as reported by Kjartanson et al. (1998). Detailed information of the buried conduit tests can also be found in the report (Kjartanson et al., 1998).

Figure 7 is the comparison of the field test data and CANDE solutions with the Young's modulus calculated from both traditional equation (1) and the new equation (22). Figure 7 indicates that the CANDE analytical program tends to over estimate the deflections. It is important to notice that although the curves from the CANDE program and the experimental data are closer using the Young's modulus calculated from the new equation than that from the traditional equation, the difference between the predictions from the traditional equation and the new equation is about 9% at the maximum deflection in Figure 7. The reason for the limited improvement is that the Young's modulus of the backfill soil has a much more significant effect on the deflection of a pipe than that of the Young's modulus of the pipe (Petroff, 1993).

Perhaps of more important significance is that equation (19) can be applied to any low-stiffness flexible pipe under parallel plate loading. Once the applicability of equation (20) has been examined by more laboratory tests, it can be extended to a much broader area than just truck tire culverts.

CONCLUSIONS

The new nonlinear stress-strain relationship derived for low-stiffness flexible pipes under parallel plate loading and the methodology developed for determining the moment of inertia of scrap tires worked well for scrap tire culverts. The analytical solutions of CANDE program obtained by applying the estimated parameters from the new equation compared favorably with the field experimental data and had a better match than those from the traditional equation. However, the broader significance of the new equation needs to be examined by laboratory tests and more practical applications as the use of low-stiffness pipes is growing rapidly.

ACKNOWLEDGMENTS

This study was funded by grants from the University of Northern Iowa, Recycling Reuse Technology Transfer Center and the Iowa Department of Natural Resources, Landfill Alternatives Financial Assistance Program. The authors gratefully acknowledge this support.

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Table 1 M_0 and c for Low-Stiffness Flexible Pipes at Deflections From 0-20%.

δ (%)	c	M_0 ($\times Pr_0$)
0	0.149	0.182
1	0.151	0.183
2	0.153	0.184
3	0.154	0.186
4	0.156	0.187
5	0.158	0.188
6	0.160	0.190
7	0.161	0.191
8	0.163	0.192
9	0.165	0.194
10	0.166	0.195
11	0.168	0.196
12	0.169	0.197
13	0.171	0.198
14	0.172	0.200
15	0.174	0.201
16	0.175	0.202
17	0.176	0.203
18	0.178	0.204
19	0.179	0.206
20	0.180	0.207

Table 2 Average Pipe Stiffness and Young's Modulus of Truck Tires at 5%, 10% and 15% of Deflections Under Parallel Plate Loading.

	5%	10%	15%
TS (kPa)	124	116	113
c	0.158	0.166	0.174
EI (kPa•m^3)	2.17	2.13	2.17

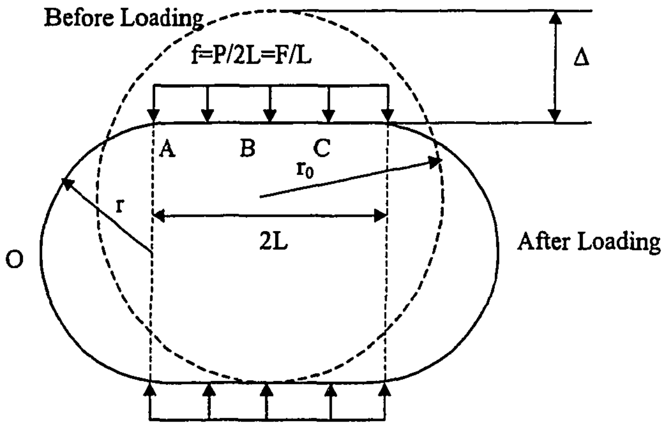


Figure 1 Low-Stiffness Flexible Pipes Under Parallel Plate Loading

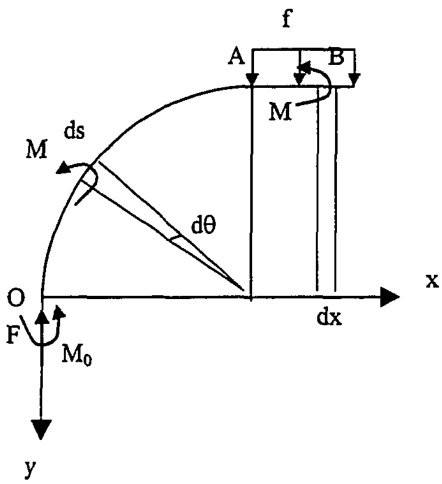


Figure 2 The Free Body Under Consideration

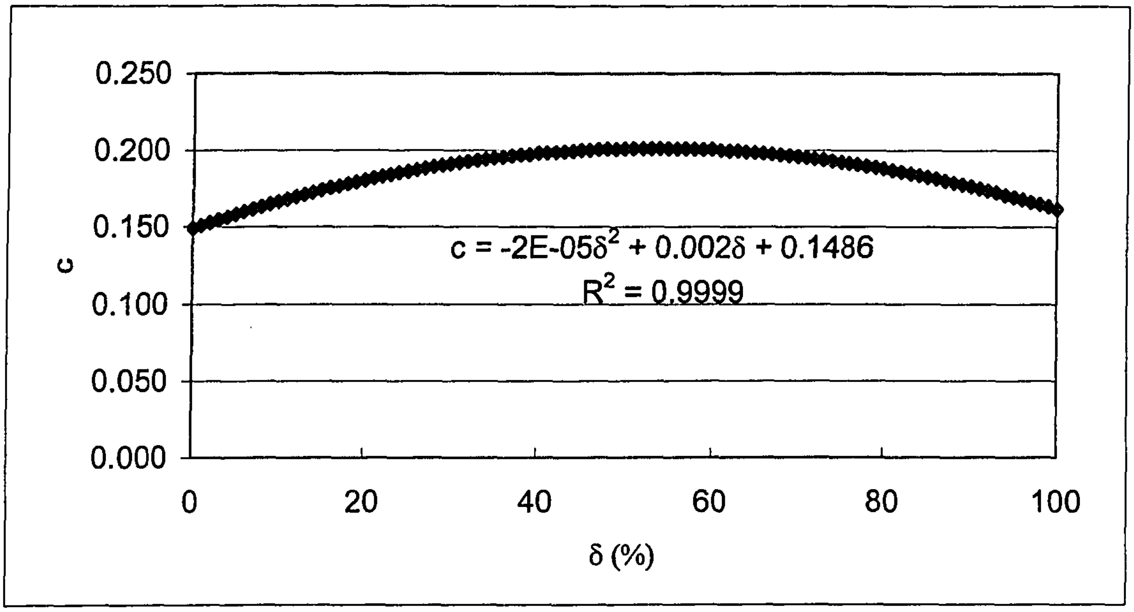


Figure 3 Relationship Between c and δ

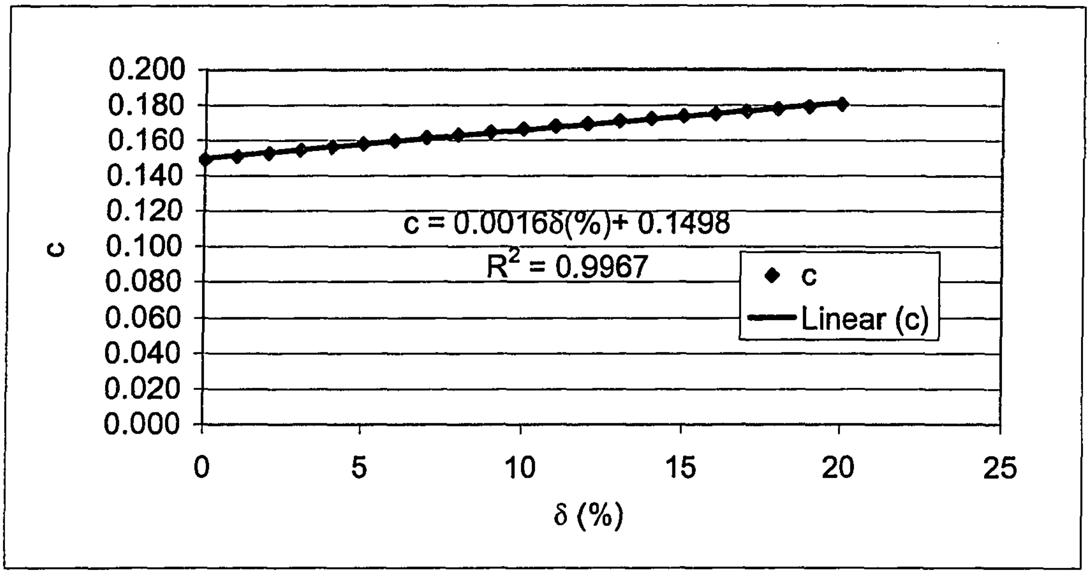
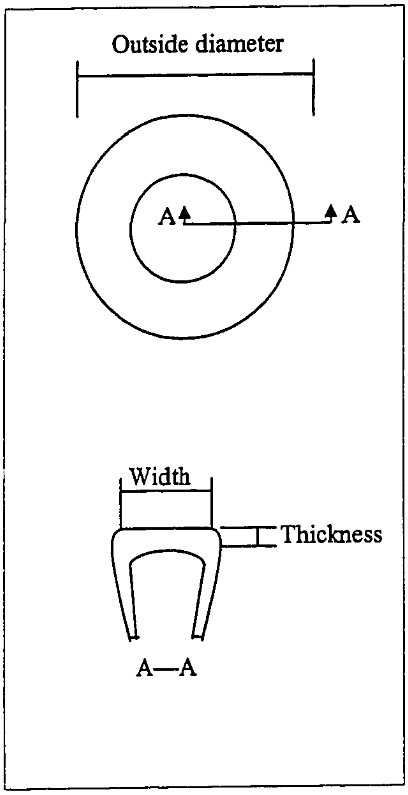
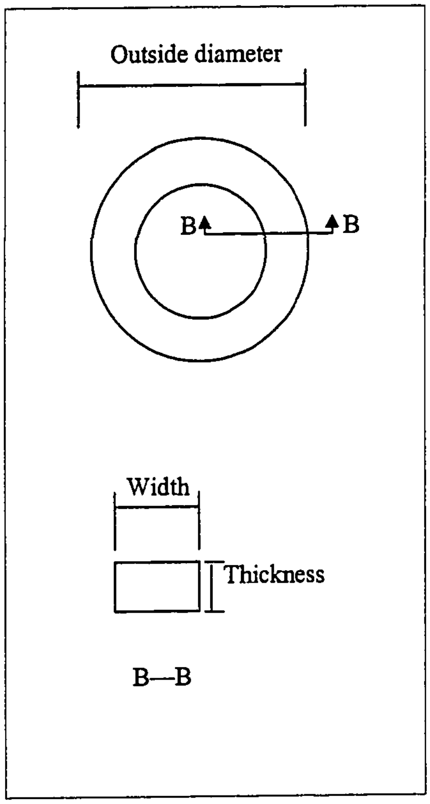


Figure 4 Linear Approximation of c and δ at Deflections From 0 To 20%



Real cross-sections of tires



Assumed cross-sections of tires

Figure 5 Determination of the Nominal Thickness For Tires

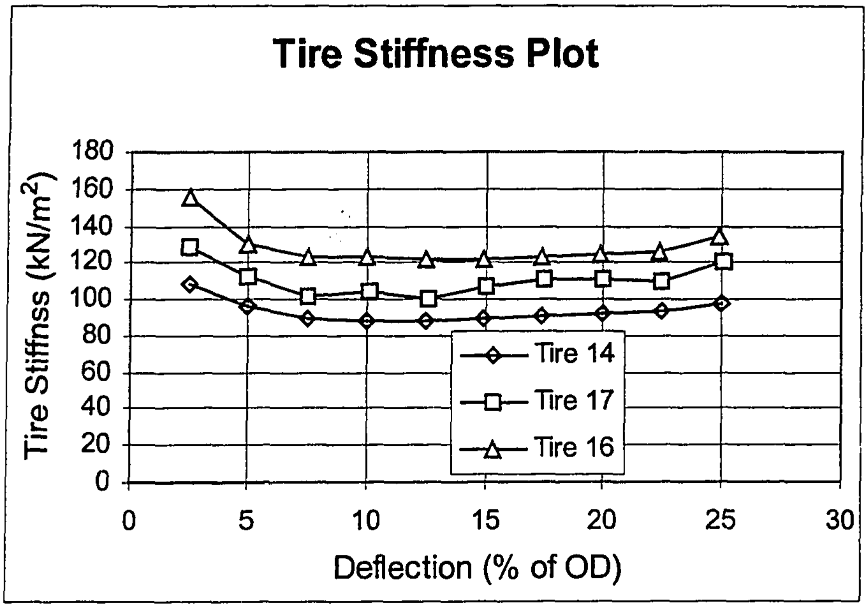


Figure 6 Typical Tire Stiffness Versus Deflection Plot

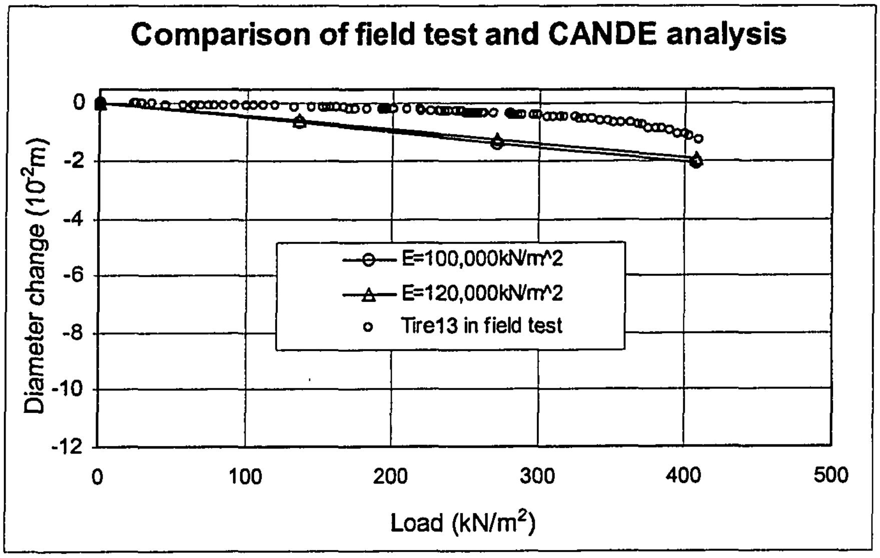


Figure 7 Comparison of Field Test and CANDE Solution

CHAPTER 5. MECHANICAL PROPERTIES OF TIRE SHREDS

A paper to be submitted to ASTM Geotechnical Testing Journal

Shiping Yang, Robert A. Lohnes, and Bruce H. Kjartanson

ABSTRACT Using scrap tires as construction materials in civil engineering is of growing interest. The design and performance evaluation of structures constructed with scrap tires require the engineering properties of tire materials. Traditional direct shear tests and triaxial tests were carried out to evaluate the mechanical characteristics of tire chips. The results, along with the existing data from previous studies, were analyzed. It was found that the shear strength of the tire chips is independent of the particle size of the material, and the strength envelope is nonlinear. The function for the strength envelope of tire chips in direct shear testing and the relationship between the confining pressure and Young's modulus of tire chips in triaxial testing were generated by integrating almost all of the available experimental results of pure tire chips. It is thought that these integrated models will have a much broader application than any individual one.

Keywords: Scrap tires, tire chips, tire shreds, direct shear test, triaxial test, Young's modulus, friction angle, cohesion intercept, Mohr-Coulomb envelope

INTRODUCTION

Shredded scrap tires have been used as constriction materials in civil engineering applications such as retaining wall backfill (Humphrey, 1993), road embankments (Bosscher et al., 1993), and subsurface drainage systems (Kjartanson, et al., 1998). The construction and design of these structures require engineering properties of the shredded tire material. A number of researchers have studied the engineering properties of shredded tires associated with the applications in civil engineering construction. Humphrey et al. (1993), Foose et al. (1996), and Gebhardt (1997) conducted independent direct shear tests on tire shreds in large-size shear machines. The sizes of the material they tested varied from 38 mm to 1400 mm. Using peak shear stress or, stress at a horizontal displacement equal to 10% or 9% of the length of the shear box if no peak stress is observed, as a failure criterion, the shear strength parameters were obtained. The friction angles obtained from these studies ranged from 19^0 to 38^0 with zero or small cohesion intercept up to 11.5 kPa.

Bressette (1984), Ahmed (1993), Benda (1995), Masad et al. (1996), Wu et al. (1997) and Lee et al. (1999) conducted independent triaxial tests on tire chips. The sizes of the material they tested were from 2 mm to 38 mm. All the tests were conducted with a compression loading mode except Wu et al. (1997), who conducted compression unloading tests. A linear stress-strain response up to 30% strain was observed from all compression loading tests. Due to the variation of confining pressure and the difference of testing mode (compression loading or unloading), the results from these studies varied significantly. The friction angle ranges from 6^0 to 57^0, and the cohesion intercept varies from 0 to 82 kPa.

All the studies mentioned above used traditional soil mechanics direct shear and triaxial testing methods to quantify the shear strength of tire chips. The results were also analyzed using the traditional Mohr-Coulomb failure envelope except Gebhardt (1997), who suggested a nonlinear power function. Due to the large range of confining pressure and particle size of the material, and the difference in sample unit weight, the shear strength parameters generated from different authors vary significantly.

The objective of this study was to conduct independent direct shear tests and triaxial tests of shredded tire material, examine the existing data of the shear strength of tire chips, and find a unified method to quantify the shear strength of tire chips.

TIRE CHIP MATERIAL

The material used in this study was "6 plus tire crumb" provided by EnTire Recycling, Inc., Nebraska City, Nebraska. This material contains no steel wires but has a very small amount of nylon fibers. The "6 plus tire crumb" material, called tire chips in this study, is poorly graded with particle sizes ranging from 2 mm to 10 mm. The gradation curves from three sieve analyses are shown in Fig. 1.

The specific gravity of the tire chips was obtained using a Helium Pycnometer. The values from three tests are 1.155, 1.152, and 1.149 with an average of 1.152. For comparison, Wu et al. (1997) obtained values on similar materials ranged from 1.08 to1.18. The Scrap Tire Management Council (1999) reported a value for the specific gravity of tire rubber of 1.15, which is very close to the average value measured in this study.

SAMPLE PREPARATION

All the samples tested were prepared with a compaction technique developed prior to the start of the experimental program. First, the desired amount of tire chips was weighed and divided into three portions of equal weight. The tire chips were then poured into the mold in three lifts or into the shear box in two lifts. Each lift of tire chips was tapped and 40 strokes with a spatula were applied. In this way a constant unit weight and initial void ratio were achieved. The initial unit weight and void ratio of all the samples were 5.73 kN/m^3 (0.585 g/cm^3 or 36.5 pcf) and 0.98, respectively.

COMPRESSIBILITY

Both confined compression and isotropic compression tests were conducted. The confined compression tests were performed in an oedometer of 63.5 mm in diameter and 25.4 mm in height. The isotropic compression tests were performed in a triaxial cell with a sample size of 71.1 mm in diameter and 149 mm in height. A short-term (test was terminated at a lower stress) and a long-term (test was terminated at a higher stress) test were conducted for both confined compression and isotropic compression. For each load increment, the load was maintained for about 10 minutes. The results of the four tests along with the data on the post consolidation states from six direct shear tests and six triaxial tests are presented in Fig.2.

Figure 2-a shows that for the two long-term tests isotropic consolidation produces larger volumetric strain. This is due to the difference of the boundary conditions between confined compression and isotropic compression. The sample in confined compression has a fixed lateral boundary, and thus produces lower volume change. However, the two curves tend to merge at a high stress level. The sample underwent about 40% volumetric strain at a stress of 480 kPa. This magnitude is similar to the confined compression test of Humphrey et al. (1993) where the sample had 40% strain at 400 kPa vertical applied stress. These small tire chips have much lower compressibility than large-sized shreds (100 – 900mm long) which exhibit 40% strain at about 17 kPa vertical applied stress (Zimmerman, 1997). The main reason for this is that the initial void ratio of Zimmerman's large tire shreds was around 3 (Fig. 3), while the initial void ratio of tire chips in this study was 0.98. Figure 2-a also shows that a sample from the triaxial test generally had a higher volume change than that from isotropic consolidation at the same confining stress. This is an effect of the sample size. Samples tested under triaxial condition were 100.6 mm by 200 mm in size, while samples tested under isotropic condition were only 71.1 mm by 149 mm in size.

Figure 2-b shows a linear relationship between the void ratio and the logarithm of stress for the long-term test for both confined compression and isotropic compression with a slight departure at low stress level when the initial points are not included.

CREEP

Due to time constraints, only one creep test was run in an oedometer. The test lasted about a month at a stress level of 46.4 kPa. The strain versus time curve is plotted in Fig. 4.

From Fig. 4-a, it is clear that the tire chips underwent 14.5% vertical strain immediately after loading (half an hour). The sample strained an additional 0.5% in the next 8 hours. The sample strained about an additional 1% in the next 20 days, and the strain rate became very small thereafter. The total vertical strain after 25 days was 16%. Fig. 4-b shows the relationship between the logarithm of strain and the logarithm of time beginning at one day after loading. A linear trend is evident in Fig. 4-b. A simple linear regression gives the following power function

$$\varepsilon_v = 15.1T^{0.0182} \qquad (1)$$

where ε_v is the total vertical strain and T is the time after loading in days.

From equation (1), the total strain after ten years of loading at 46.4kPa would be 17.5%.

DIRECT SHEAR TESTS

Seven direct shear tests were conducted at normal stresses of 0, 20.7, 41.4, 62.1, and 82.7 kPa with a 63.5 mm diameter shear box at a shearing displacement rate of 1 mm/min. Before the shear stress was applied, the samples were consolidated under the applied normal stress until the vertical strain became relatively stable. Fig. 5 shows the shear stress and volume change (vertical strain) versus horizontal displacement for these tests. None of the tests have well-defined peaks after up to 20 mm of shear displacement (31.5% of the diameter of the shear box). The general shape of the curves is similar to that presented by Humphrey et al. (1993). During shearing, the samples initially compressed and then began to dilate after about 5 mm to 13 mm of displacement, depending on the applied normal stress (Fig. 5-b). The volume change was between 1.6% (compression) and -1.8% (dilation). The results from consolidation are plotted in Fig.5-c.

The shear strength of the tire chips was analyzed using traditional Mohr-Coulomb theory. Since no peak shear stress was observed, the shear stresses at a displacement of 10%, 20%, and 30% of the diameter of the shear box were plotted for each test. The results are shown in Fig. 6. Generally, the stress at a displacement of 10% of the width of the shear box has been used to define the strength of the material if no peak stress occurred during shearing (AASHTO, 1986). When applied to these tire chips, it gives a friction angle of 32° with zero cohesion intercept.

As mentioned earlier, all of the samples underwent a compression and then dilation process, or reached a minimum volume during the shearing. Since a sample was forced to shear along a certain plane in a direct shear test, the minimum volume represents the point where the sliding friction between particles start to be fully mobilized. Using the minimum volume of a sample as a failure criterion, the shear strength of tire chips was obtained by fitting a straight line through 0 (Figure 6). This yields a higher friction angle of 40.7° than the 10% criterion.

The Mohr-Coulomb shear strength parameters obtained from direct shear tests by other researchers range from 19° to 38° for friction angle and from 0 to 11.5 kPa for cohesion intercept as shown in Table 1. Figure 7 is a shear stress versus normal stress plot of all the data points from the four authors listed in Table 1. From Table 1 and Figure 7, one can conclude that: 1) the shear strength of tire shreds appears independent of the particle size; 2) the friction angle seems larger at lower normal stresses where a zero cohesion intercept has been interpreted; 3) all of the authors used a similar failure criterion. These imply that all the data from different researchers can be analyzed without considering the effect of particle size, and it is not appropriate to fit one simple linear function for the entire normal stress range for tire chips. A power function is fitted to the data in Figure 7. An R-square value of 0.9363 indicates a good fit. From the fitted power function

$$\tau = 1.6\sigma^{0.75} \ , \qquad (2)$$

the friction angle at stresses up to 90 kPa can be obtained

$$\phi = \tan^{-1}(1.2\sigma^{-0.25}) \ . \qquad (3)$$

Equation (3) indicates that the friction angle of tire chips decreases with increasing normal stress.

Gebhardt (1997) first fitted a power function on the similar data and obtained the following relationship

$$\tau = 1.4\sigma^{0.79}. \qquad (4)$$

Both equation (2) and equation (4) are plotted it Figure 7-b along with the data used in this analysis. It can be seen from Figure 7-b that both equations (2) and (4) fit the data well and have identical predictions at normal stresses less than 40kPa. Equation (4) tends to give a higher strength at normal stress beyond 40kPa. The difference increases as the normal stress increases.

DIRECT SHEAR TESTS ON TIRE DISCS

To better understand the characteristics of the shearing response of tire chips, the frictional characteristics between two flat tire discs was measured. Ten 63.5mm diameter discs were cut from the sidewalls of a used tire. Direct shear tests were conducted using the same machine used for tire chips. Two pieces of tire disc were used for each test. The discs were sheared along their interface. The shear stress versus horizontal displacement response is shown in Fig.8.

From Fig.8, it is seen that for all the tests, the shear stress increases almost linearly up to 2.5-3.5mm of displacement, and then becomes constant thereafter. The friction angles were calculated to be 35°, 38° and 40° at confining pressures of 41.4, 62.1, and 82.7kPa, respectively, indicating a higher friction angle at higher normal stress. An average friction angle of 38.5° is obtained from the regression of a straight line passing through zero (Fig. 9). This average friction angle is larger than the friction angle of the tire chips obtained from direct shear tests at 10% horizontal displacement, which is 32°, but is smaller than those obtained at 20% and 30% horizontal displacement, which are 41.5° and 45°, respectively. Since the friction angle of 38.5° measured from the tire discs represents the sliding friction between the surfaces of tire particles, the rolling friction angle between tire particles would be far less than 38.5°. The fact that the friction angle of tire chips is smaller than 38.5° at smaller displacement and larger than 38.5° at greater displacement reflects that the rolling friction among tire particles dominate in the early stage of shearing and the sliding friction can only be mobilized at a large displacement after the minimum volume has been reached. From Figure 5-b, the samples of tire chips generally reached their minimum volumes after about 15% displacement. The friction angle of 40.7° obtained at the minimum volume confirms the above hypothesis.

TRIAXIAL TESTS

Triaxial tests were used in this study to measure the strength and stress-strain response of tire chips. The samples were prepared in a 100.6 mm diameter by 200 mm high rigid split-mold placed on the triaxial cell pedestal. A suction (less than or equal to the desired confining pressure) was applied using a vacuum pump before the mold was removed. The samples were loaded axially under a displacement-controlled mode where the rate of axial deformation was set at 0.635mm/min. The applied axial load and the corresponding axial displacement, volume change, and cell pressure were recorded with a data acquisition system. A total of 5 tests were conducted and the results are plotted in Fig. 10.

Fig. 10-a shows the deviator stress-axial strain characteristics of the tire chips. The shape of the curves is nearly linear. No peak stress was reached for all the five tests, and no failure plane was observed in the samples during the tests. This stress-strain response is similar to that found by other researchers (Ahmed, 1993; Benda, 1995; Masad et al., 1996; and Lee et al., 1999) where the stress-strain response is almost linear for up to 30% of strain. However, no evidence of strain hardening was found in this study as was observed by Ahmed (1993) and Masad et al. (1996).

An unloading test was carried out at a confining pressure of 68.3kPa. The sample was loaded to about 22% strain and then the axial load was decreased. The data show that about 10% permanent strain occurs after the load is released.

Fig. 10-b shows volume change versus axial strain for the five tests. All the samples experienced volumetric compression during the tests. The curves are all linear up to about 10% axial strain. The rate of volume change decreases slightly after that. This volume change character is consistent with the results of Benda (1995), Masad et al. (1996), and Lee et al. (1999).

Through linear regression on the stress-strain curves in Figure 10-a, the Young's moduli of tire chips were obtained to be 718, 840, 874, and 924 kPa at the confining pressures of 42.1, 64.1,68.3, and 88.3 kPa, respectively. The shear stresses at 10% and 20% strains calculated from the linear regression functions were used for strength analysis. A p-q plot is shown in Figure 11. The friction angle and cohesion intercept obtained from Figure 11 are 11.0° and 21.6 kPa and 18.8° and 37.7 kPa at 10% and 20% strains, respectively. These results are similar to those reported by Ahmed (1993).

Table 2 lists the shear strength parameters obtained from 7 different triaxial test studies. All the authors conducted compression loading tests except Wu (1997) who conducted compression unloading tests. Due to the large range of confining pressure (from 23 kPa to 350 kPa) and the difference of test methods (compression loading or unloading), the fitted values of cohesion intercept and friction angle from different authors vary significantly. This implies that the Mohr-Coulomb criterion may not be appropriate to characterize the shear strength of tire chips.

Since the stress-strain response is linear for tire chips under triaxial loading, the study of Young's moduli of tire chips under different confining pressures is useful for characterizing the strength of tire chips. The Young's modulus, E, is defined as:

$$E = \frac{\Delta(\sigma_1 - \sigma_3)}{\Delta\varepsilon_1} \qquad (5)$$

where σ_3 is the confining pressure, and σ_1 and ε_1 are the axial stress and strain, respectively.

Figure 12 is a Young's modulus versus confining pressure plot for the data from five studies in Table 2. It is suggested in Fig.12 that the Young's modulus, E, increases with increasing confining pressure. But the rate of increase becomes much lower at high confining pressures. Figure 12 also implies that both particle size and initial unit weight of tire chips do not have a significant effect on the Young's modulus. However, the variations of particle size (2-51 mm) and unit weight (4.95-6.75 kN/m^3) here were not very significant compared with those data from direct shear tests. A quadratic function is fitted to the data in Figure 12:

$$E = 13.2\sigma_3 - 0.0191\sigma_3^2 . \qquad (6)$$

Equation (6) is the result of an integration of all the data available in the literature. It can be used to calculate the Young's modulus of tire chips for the confining pressure up to 350 kPa and strain up to 20% Once the Young's modulus is determined, the strength of tire chips at a certain strain level can be obtained.

CONSLUSIONS

The shear strength of tire shreds has been investigated by a number of researchers. The results of this study are similar with those of previous studies. In terms of the stress-stain response and shear strength of tire shreds, the following conclusions are drawn.

For Direct Shear Tests

1. The stress-strain curves were nonlinear, and no well-defined peak stress was observed for most of the tests.
2. A friction angle of 32^0 with a zero cohesion intercept was obtained using 10% displacement as a failure criterion.

3. Samples were compressed in the early stage of shearing and started to dilate after about 15% displacement.
4. Rolling friction dominates the shearing process in the early stages, and sliding friction can only be mobilized after the minimum volume is reached.
5. A friction angle of 40.7^0 was obtained with zero cohesion intercept using minimum volume as a failure criterion.
6. Particle size does not affect the shear strength.
7. The strength envelope is nonlinear (equation (2)).
8. The power function (equation (2)) is a result of an integration of all the test results available in the literature, and thus has broader application.

For Triaxial Tests

1. The stress-strain response is linear up to 20% strain.
2. No obvious failure plane was observed in the samples.
3. The samples underwent compression during the axial loading, and the volume change versus axial strain is almost linear up to 20% axial strain.
4. The friction angle and cohesion intercept were found to be 11.0^0 and 21.6 kPa, and 18.8^0 and 37.7 kPa, respectively, at a axial strain level of 10% and 20%.
5. The particle size and unit weight do not have a significant effect on the stress-strain response or the Young's modulus.
6. The quadratic function (equation (6)) is the result of an integration of all the test results available in the literature, and thus has broader application.

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Table 1 Shear Strength of Tire Chips From Direct Shear Testing

Author	Maximum size (mm)	Unit weight (kN/m^3)	Normal stress (kPa)	Cohesion intercept (kPa)	Friction angle (°)	Criterion of failure stress
Humphrey et al. (1993)	51	6.30	17-68	7.7	21	Peak or at 10% disp.*
	76	6.08	17-63	11.5	19	
	38	6.06	17-62	8.6	25	
Foose et al. (1996)	50,100,150	NA	1-76	3	30	Peak or at 9% disp.*
Gebhardt (1997)	1400	NA	5.5-28	0	38	10% disp.
This study	10	5.73	0-83	0	32	10% disp.

* The failure was considered to be the peak shear stress or, if no peak was reached, the shear stress at a horizontal displacement equal to 10% (or 9%) of the length of shear box was taken.

Table 2 Shear Strength of Tire Shreds From Triaxial Testing

Author	Maximum size (mm)	Unit weight (kN/m^3)	Confining pressure (kPa)	Failure criterion and shear strength							
				10% strain		20% strain		Maximum		NA	
				c (kPa)	ϕ	c (kPa)	ϕ	c (kPa)	ϕ	c (kPa)	ϕ
Benda (1995)	38	5.89	35-55	0	21.1	0	35.5				
	19	5.62	35-55	0	21.4	0	34.1				
	9.5	4.95	35-55	0	17.2	0	31.2				
	9.5	5.88	35-55	0	20.6	0	32.1				
	2	5.23	35-55	0	25.8	0	36				
Ahmed (1993)	13	6.19	36-199	22.7	11.2	35.8	20.5				
	25	6.32	31-199	25.4	12.6	37.3	22.7				
	25	6.42	32-307	22.1	14.6	33.2	25.3				
	25	6.75	32-199	24.6	14.3	39.2	24.7				
Masad et al. (1996)	4.75	6.24	150-350	70	6	82	15				
Wu et al. (1997)	38	5.89	35-55					0	57		
	19	5.62	35-55					0	54		
	9.5	4.95	35-55					0	60		
	9.5	5.88	35-55					0	47		
	2	5.23	35-55					0	45		
This study	10	5.73	23.4-84.1	21.6	11.0	37.7	18.8				
Bressette (1984)	51	5.98	NA							25.9	21
	51	5.96	NA							31.6	14
Lee et al. (1999)	30	6.3	28-193							7.6	21

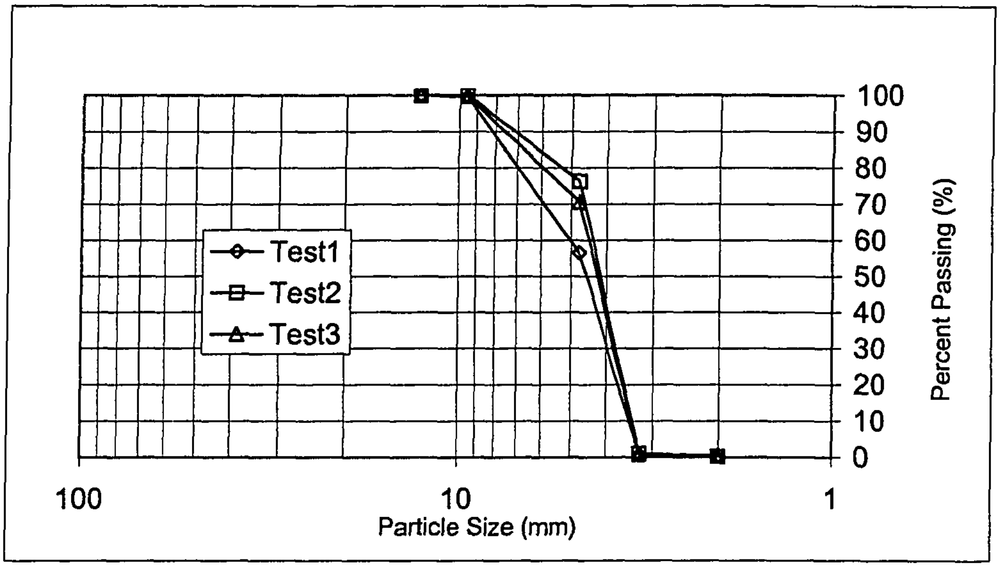

Figure 1 Gradation of Tire Chips

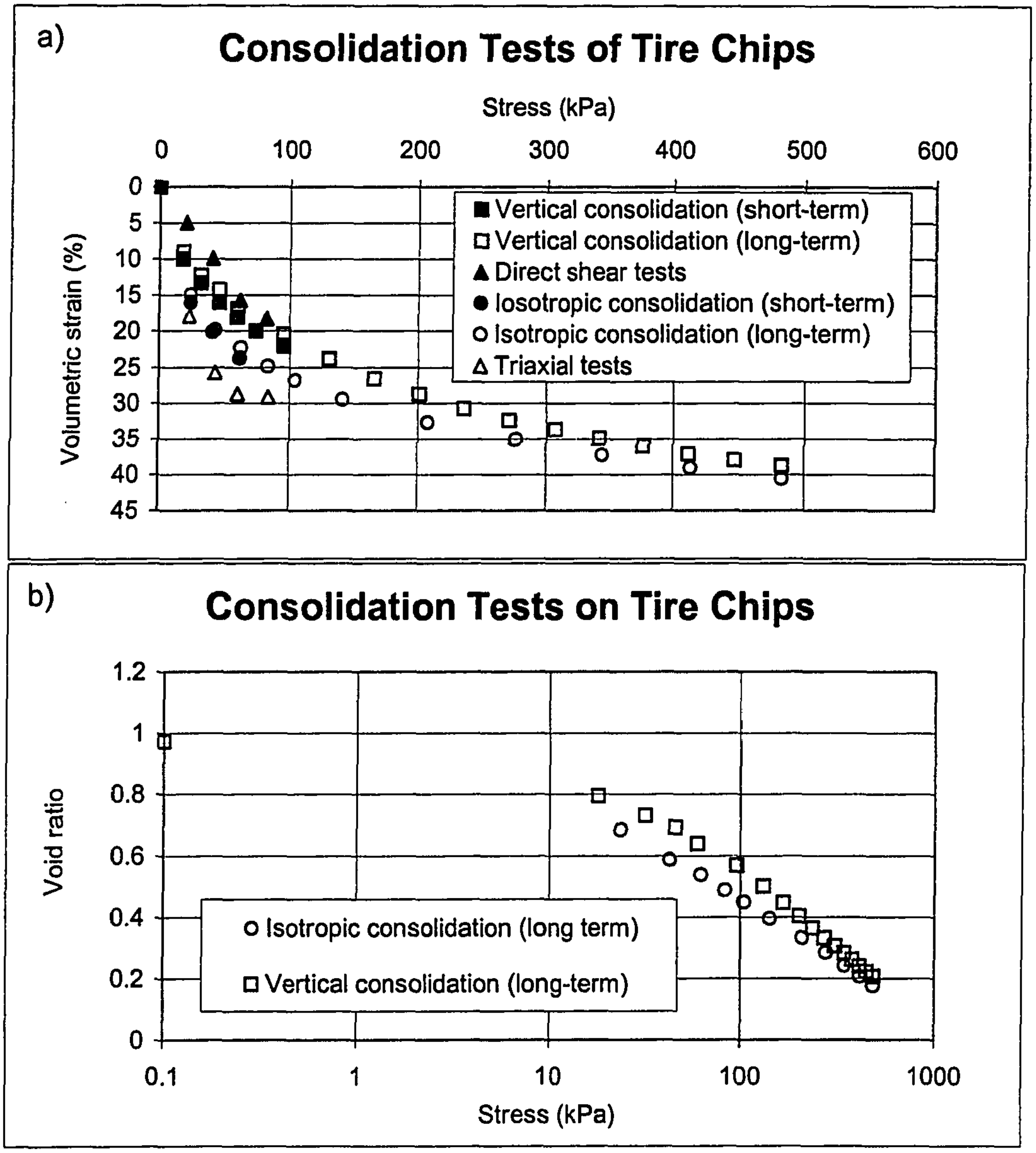

Figure 2 Consolidation Tests of Tire Chips

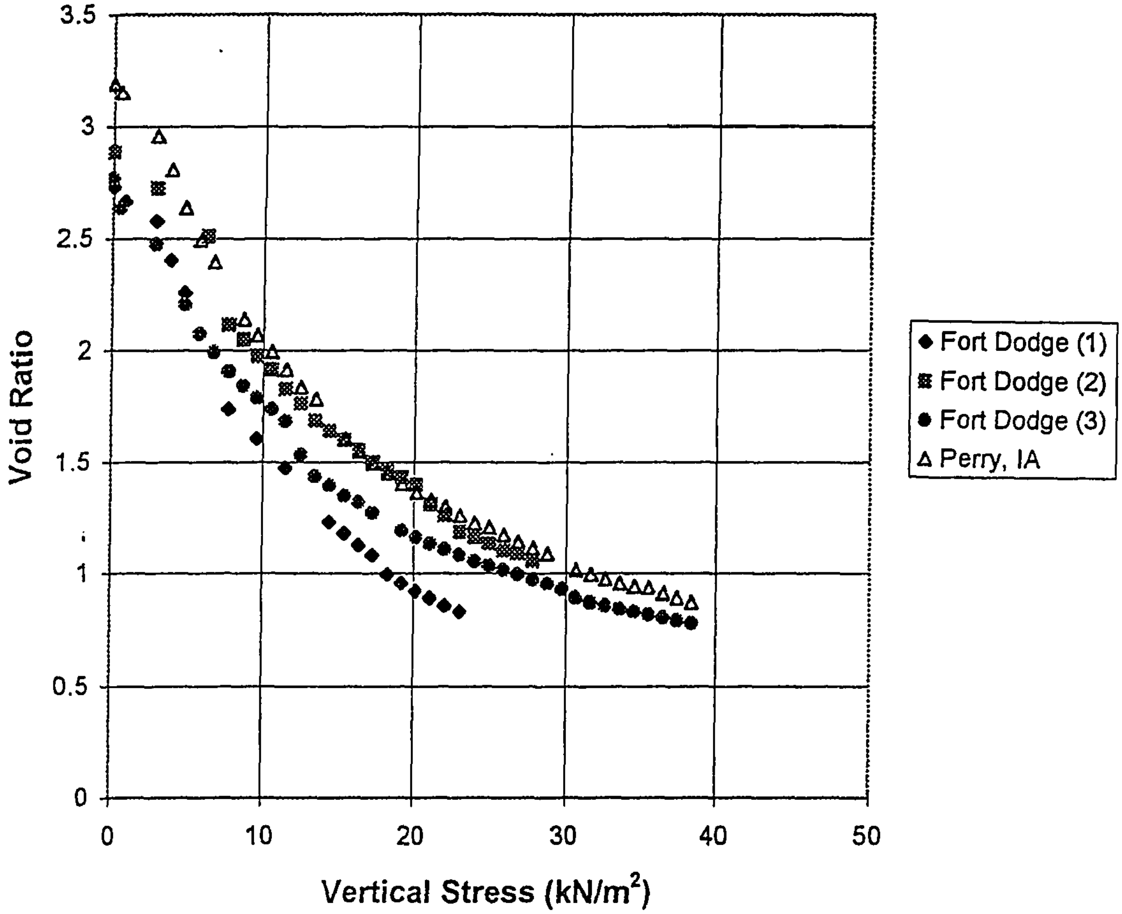

Figure 3 Void Ratio of Tire Shreds As A Function of Vertical Stress (From Zimmerman (1997))

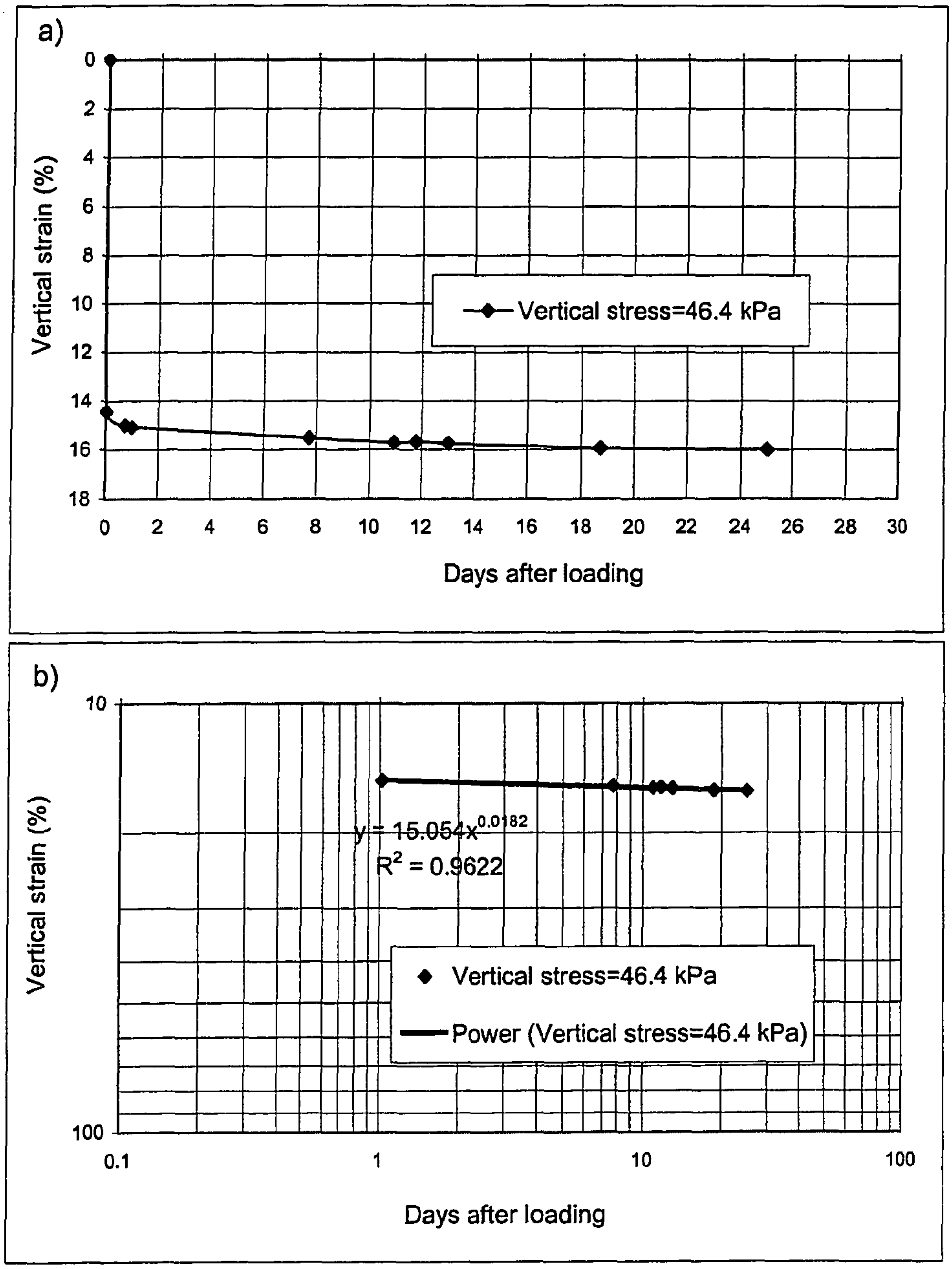

Figure 4 Creep Test of Tire Chips

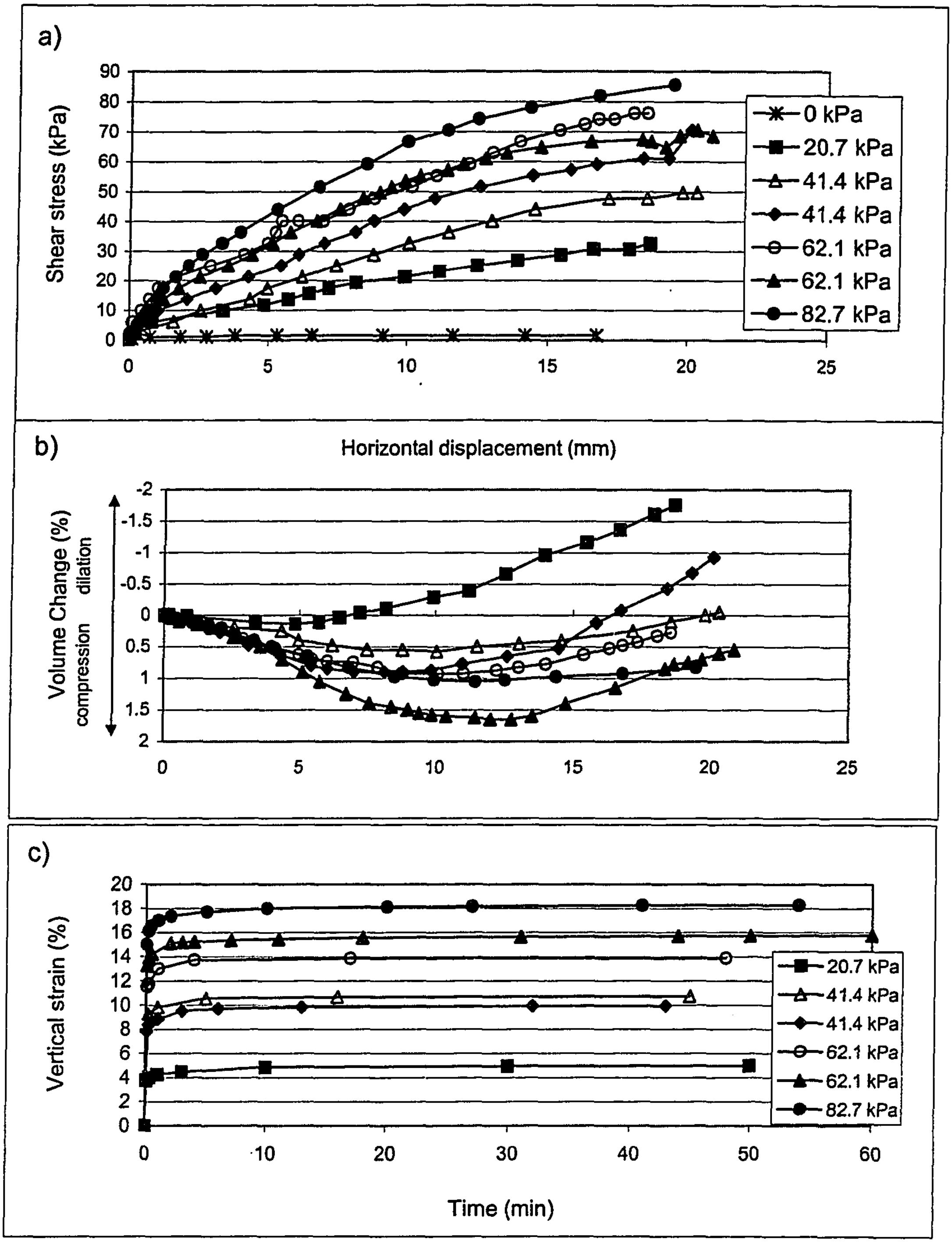

Figure 5 Direct Shear Tests of Tire Chips

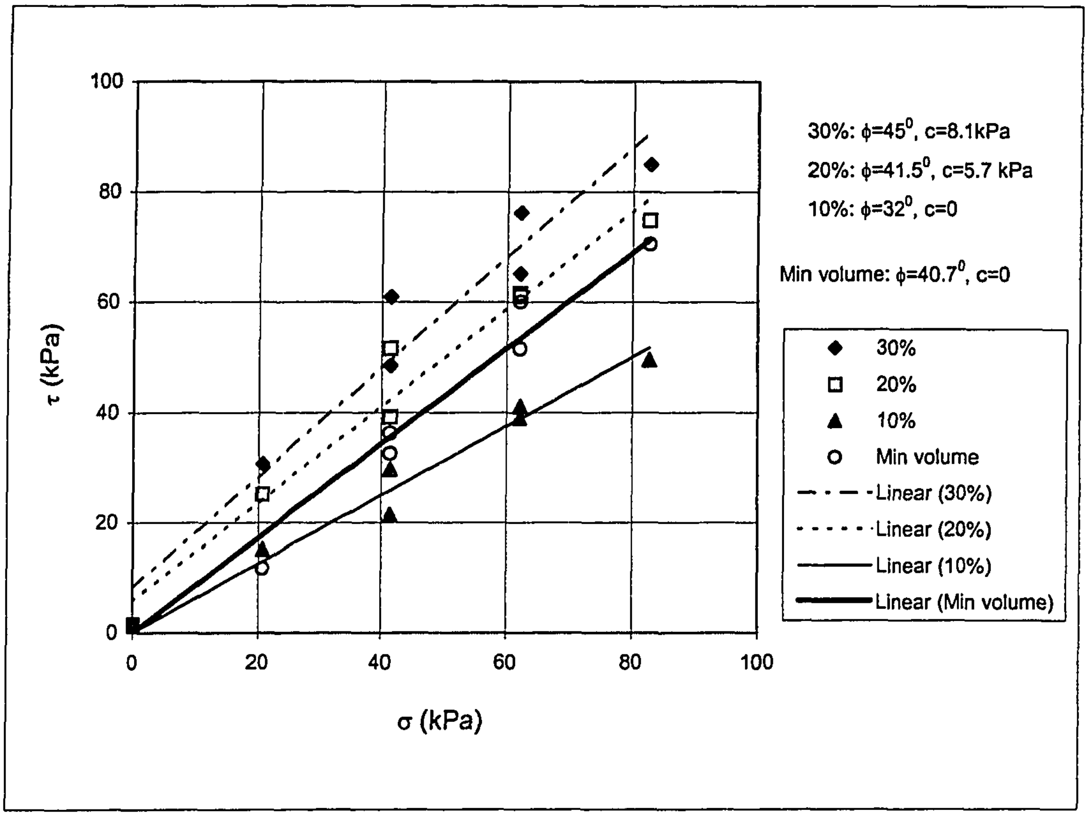

Figure 6 Shear Strength of Tire Chips from Direct Shear Tests

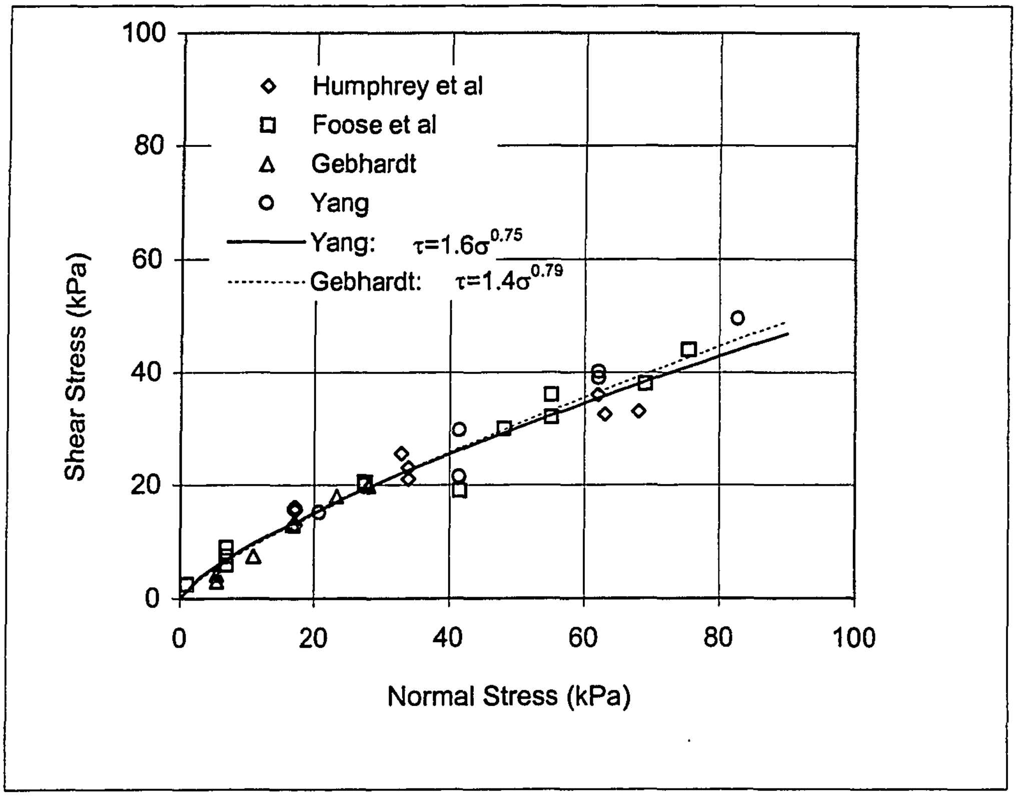

Figure 7 Shear Strength Envelope of Tire Shreds From Direct Shear Tests

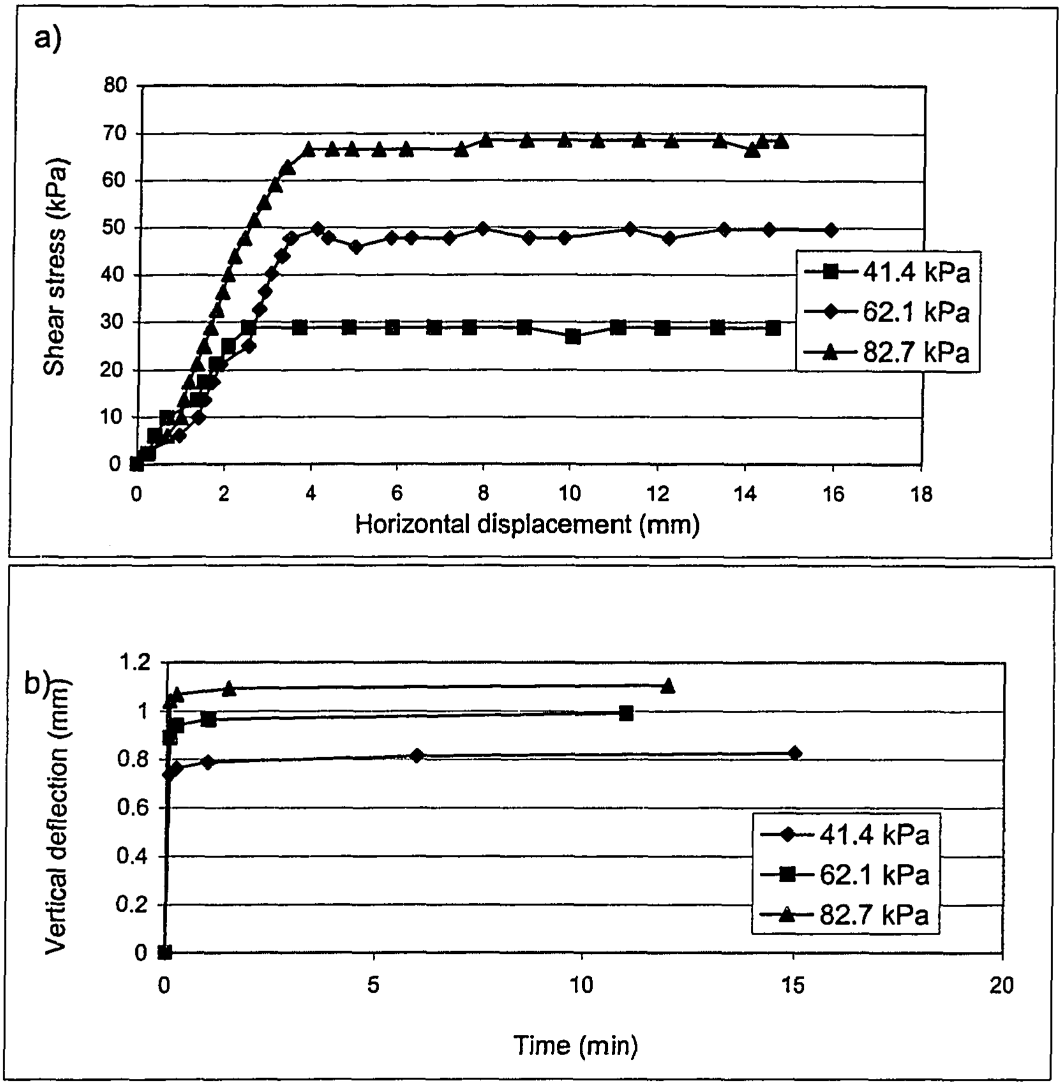

Figure 8 Direct Shear Tests of Tire Discs

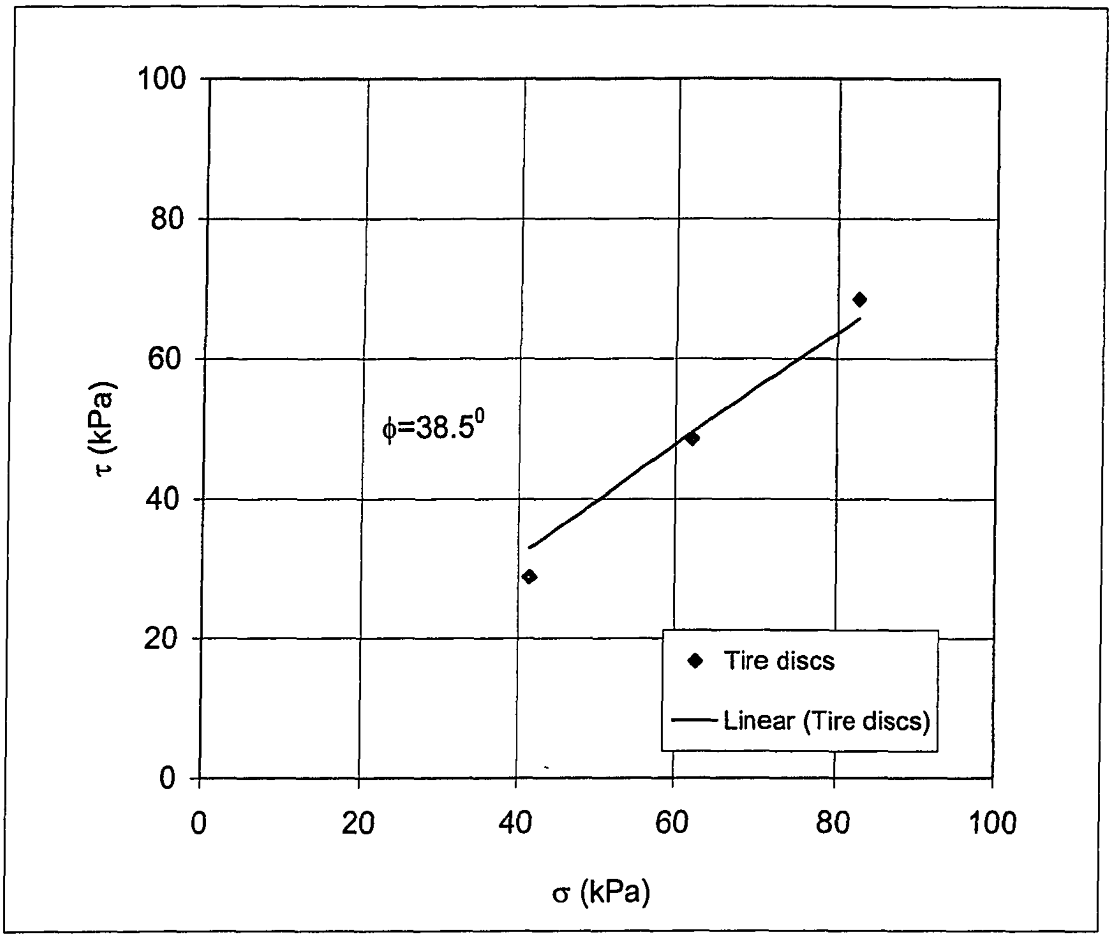

Figure 9 Friction Angle of Tire Discs

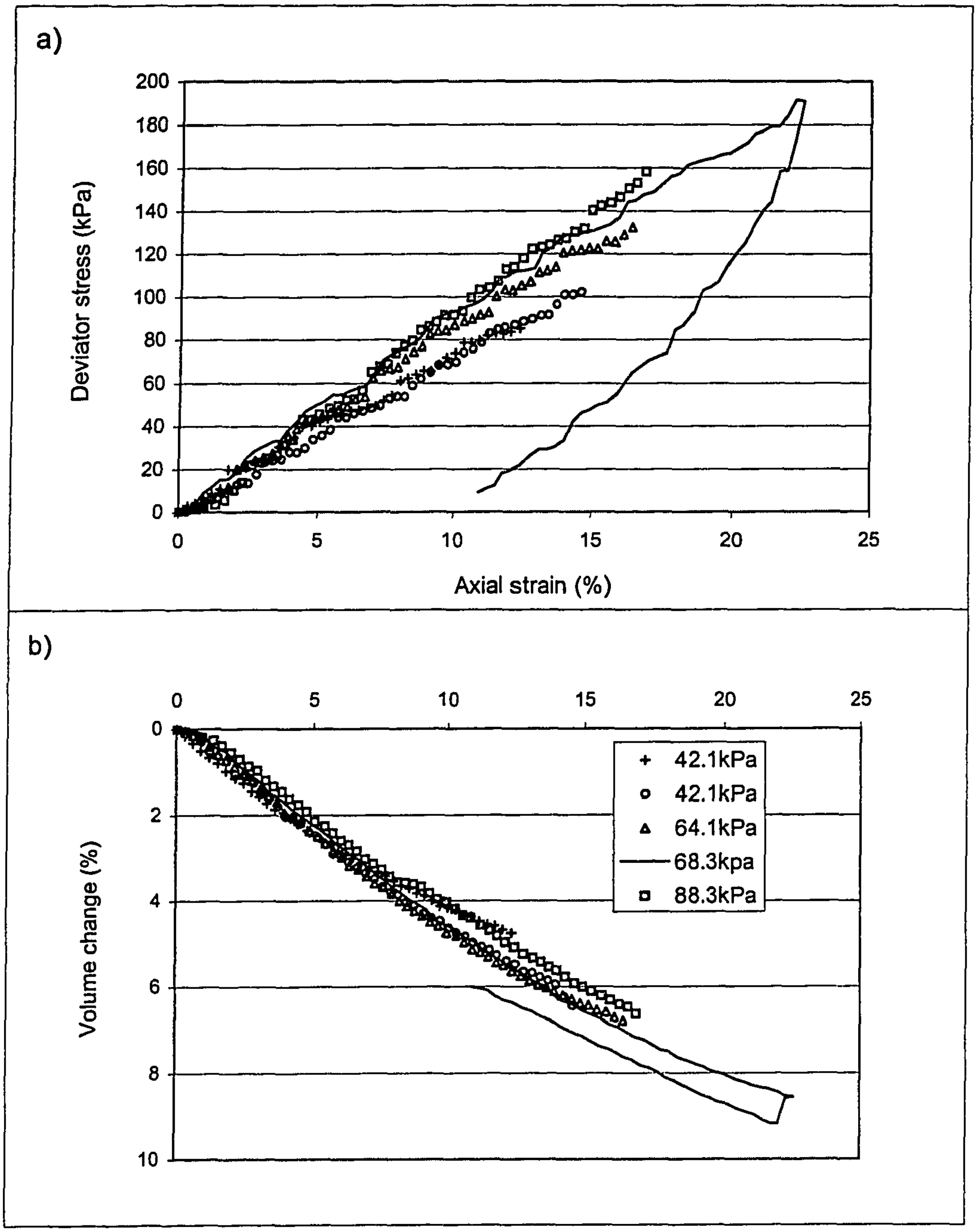

Figure 10 Triaxial Tests of Tire Chips

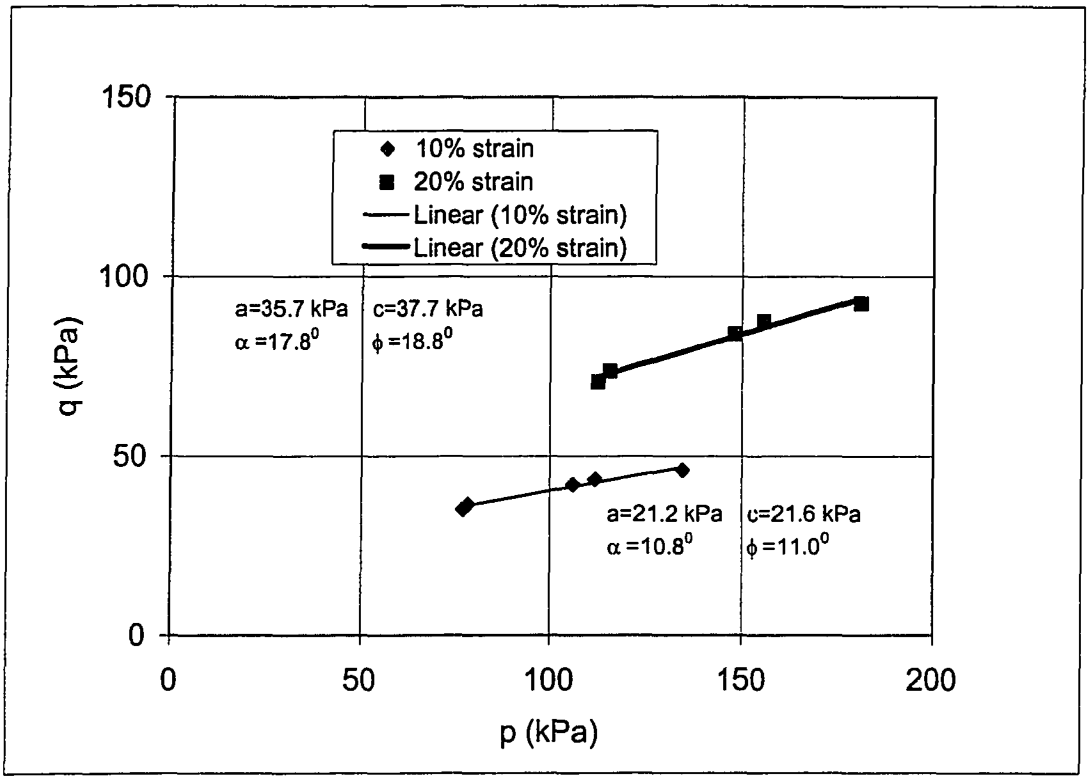

Figure 11 Shear Stength of Tire Chips From Triaxial Tests

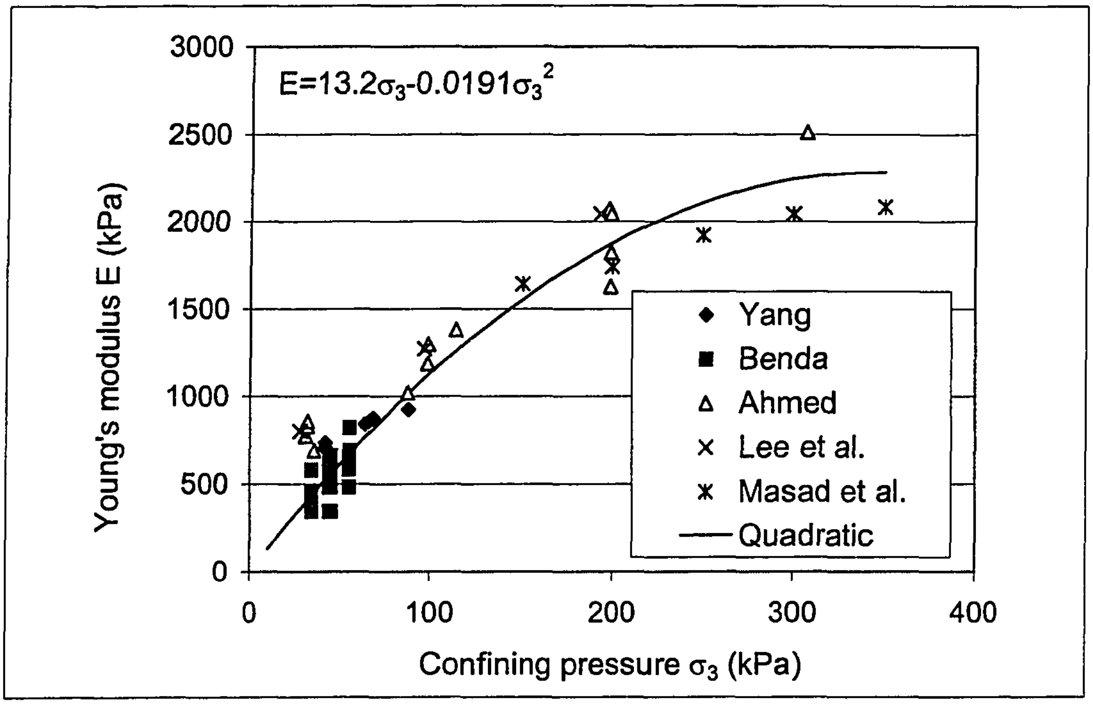

Figure 12 Relationship Between Young's Modulus and Confining Pressure of Tire Chips in Triaxial Tests

CHAPTER 6. GENERAL CONCLUSIONS

Conclusions

Using scrap tires as construction materials in civil engineering is of growing interest. Whole scrap tires have been used as culverts, retaining walls, and for slope and beach stabilization. Shredded tires have been used as horizontal drains, ravine crossings, highway embankments, lightweight backfill, and road bed support. The engineering properties of both whole and shredded scrap tires were investigated in this research.

Reusing whole scrap tires as a culvert is a cost-effective alternative to drain water from small drainage basins. The complete design of a scrap tire culvert must consider both structural and hydraulic performance.

The hydraulic capacity of a scrap tire culvert is largely affected by the limited size and the relatively rough barrel formed by scrap tires. In this research, the hydraulic capacities of culverts made of truck tires, at various slopes and lengths, were obtained by estimating Manning's roughness coefficient and limiting the maximum flow depth in the culvert to 75% of the pipe diameter. The Manning's roughness coefficient of a truck tire culvert was estimated to be 0.05 and 0.075 with and without sand ballast placed in the bottom of tires, respectively. The results show that a truck tire culvert can drain water up to 0.35-m^3/s, and its hydraulic efficiency approaches that of conventional pipes of the same diameter when the slope is greater than 0.11 or 0.30 for culverts made of truck tires with or without sand ballast, respectively. The equivalent concrete and corrugated metal pipe sizes were obtained for corresponding flow capacities of truck tire culverts.

Scrap tire culvert structural performance depends on the strength and stiffness of the truck tires as well as their interaction with the surrounding backfill soil. The strength and stiffness properties of truck tires were determined by parallel plate testing. Buried conduit field tests were conducted to evaluate the soil-structure interaction under a relatively shallow backfill condition. Responses with well compacted and uncompacted (dumped) glacial till backfill soil were compared. Drawing on the results of the parallel plate tests and using the buried conduit test results for calibration, the Culvert ANalysis and DEsign (CANDE) program was used to assess the load response of a truck tire culvert for a variety of backfill soils and the maximum and minimum backfill depths of truck tire culverts were calculated.

The traditional equation for determining the flexural Young's modulus is not appropriate for very flexible pipes such as scrap tire culverts due to their high compressibility. A new equation governing the load and deflection relationship of low-stiffness flexible pipes under parallel plate testing is derived. This equation is applied to whole scrap tires used for constructing underground culverts, and the pipe stiffness factor is calculated. In order to obtain the Young's modulus of a scrap tire culvert, the moment of inertia of the cross section of a tire must be determined. Due to the irregular cross sectional area of scrap tires, the calculation of the moment of inertia is difficult. A method was proposed to estimate the moment of inertia through measurement of physical properties of a scrap tire. The flexural Young's modulus of a scrap truck tire was then determined from the new equation. The estimated parameters were used in the CANDE program to analyze field buried conduit tests. The results using the flexural Young's modulus from the new equation compared more favorably with the field testing data than those calculated from the traditional equation. Although the new equation was derived for a scrap tire culvert, it is applicable to any low-stiffness pipe.

Using shredded tire chips as construction materials in civil engineering is another applications of scrap tires. The mechanical characteristics of tire chips were evaluated through traditional direct shear tests and triaxial tests. The results, along with the existing data from previous studies, were analyzed. It was found that the shear strength of the tire chips is independent of the particle size of the material. The rolling friction among tire particles dominate in the early stage of shearing and the sliding friction can only be mobilized at a large displacement after the minimum volume has been reached. The strength envelope of tire shreds is nonlinear. By integrating almost all of the available experimental results of pure tire chips, the empirical function for the strength envelope of tire chips in direct shear testing was found to be $\tau = 1.6\sigma^{0.75}$ and the empirical relationship between the confining pressure and initial Young's modulus of tire chips in triaxial testing was found to be $E = 13.2\sigma_3 - 0.0191\sigma_3^2$. It is thought that these integrated models will have a much broader application than any individual one.

Recommendations for Future Research

To encourage the use of scrap tires in civil engineering applications further investigations on the engineering properties of whole scrap tires and shredded tires are necessary. These recommended researches are summarized below.

1. Laboratory verification of roughness coefficients estimated in this research is necessary for more accurate hydraulic analysis on scrap tire culverts.
2. Monitoring the hydraulic and structural performance of a truck tire culvert is needed to verify the design guidelines developed in this research.
3. Examining the new stress-strain relationship of low-stiffness flexible pipes laboratory tests and more practical applications.
4. Investigation of the time-dependent, viscoelastic properties of scrap tire culvert and shredded tire materials.
5. The strength and stress-strain response of tire chip materials need to be further investigated.
6. The models for predicting the shearing resistance of tire chips developed in this research needs to be examined and verified by field applications.

APPENDIX. DESIGN GUIDELINES FOR TRUCK TIRE CULVERT

Iowa Department of Natural Resources
Landfill Alternatives Financial Assistance Program
And
University of Northern Iowa
Recycling and Reuse Technology Transfer Center Program

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Introduction

A truck tire culvert, an underground conduit built with whole scrap truck tires, is an economical alternative to a conventional underground culvert in situations where the water flow rate will be low to moderate. The structural and hydraulic characteristics of truck tire culverts have been evaluated through field tests, laboratory experiments, and theoretical analyses. These design guidelines are based on those test results and analyses.

Assumptions, Criteria and Limitations

Design assumptions, criteria and limitations set forth in the narrative are used to insure the constructability and performance of the structure. The assumptions, criteria and limitations are:

- Truck Tire Culvert (Pipe) Diameters:
  More than 60 whole scrap truck tires were measured and tested in this research. The truck tire inside diameter for conducting water ranges from 0.53m to 0.60m (21"-23.8"). The smallest diameter (0.53m) is used as the pipe diameter in the hydraulic calculations. The outside diameters range from 0.99m (39") to 1.07m (42") with the most common being 1.02m (40"); therefore it is used as the pipe outside diameter.

- Roughness coefficient:
  The roughness coefficient is an important parameter for hydraulic analyses, however no tests were carried out to measure the roughness coefficient of the truck tire culvert. Because of the extremely rough barrel formed by truck tires, the roughness coefficient was estimated by taking the highest value found in the literature and multiplying it by a factor of 2, which gives a value of 0.05.

- Maximum water depth:

  A truck tire culvert is designed for partial flow only due to the high roughness coefficient and to avoid buoyancy effects associated with air trapped in the top of the tires. The maximum water depth inside the pipe is limited to 75% of the pipe diameter (0.4m).

- Maximum pipe deflection:

  From previous studies, the design strain for HDPE pipes ranges from 4% to 8% of the pipe diameter. Tires strain more than HDPE pipes and have potential creep development; therefore, the maximum deflection of the top of tires under backfill soil and surface loading is limited to 5% of the outside diameter (0.05m).

- Minimum and maximum soil covers:

  The range of soil depths over the tires is limited by the allowable pipe deflection, which is determined by the type and degree of compaction of the backfill soil, and the surface load. With the constraint of pipe deflection less than 5% of the outside diameter, the minimum and maximum soil covers for three soils at different degrees of compaction were obtained using the CANDE analysis program.

  Important properties of the soils used in the CANDE analyses are listed in Table 1. The minimum soil covers listed in Table 2 were estimated under both soil load and H15-truck load. The maximum soil covers listed in Table 3 were estimated under geostatic load only because the effect of surface load for deep trenches is negligible.

- Tire selection:

  From the testing of more than 60 randomly selected scrap truck tires, most of the tires are adequate for culvert construction. One exception is the tires without treads (bald tires). Bald tires usually have low stiffness and may have larger deflections.

- Tire installation:
  The most convenient way to place truck tires in the trench is using sections of three banded tires. Tires are more stable and can be installed faster when banded. Sections of four or more banded tires are difficult to handle and are not recommended. In addition, it is recommended that sand ballast be placed in the bottom portion of the tires up to the top of the sidewall. This will significantly reduce the amount of water that could stagnate in this portion of the tires and also provide additional resistance to potential buoyancy effects. To further mitigate potential uplift buoyancy problems, the truck tire culverts should not be installed below the highest groundwater table position in the surrounding soil.

- Factor of safety:
  No factor of safety is applied within the design process. This is left up to the designer to determine for specific situations. However, the assumptions and limitations used here are based on conservative considerations.

Design process

Following the design flowchart, Figure 1, the first step in the design process is to gather all pertinent data about the project site. The information should include a plan view of the site, the drainage area, culvert alignment, ground surface elevations, elevations at the inlet and outlet, tailwater level, soil types, trench depth and backfill method, and types and magnitudes of surface loads.

Profile drawings using the elevation data will help the designer visualize the project and determine the gradient of the proposed tire culvert. The discharge to the culvert is proportional to the drainage area and can be determined using a runoff chart, as described below. The length and slope of the culvert determine the flow conditions and hence the hydraulic capacity of the culvert. Soil types, trench depth and degree of compaction are parameters needed for determining the pipe deflection under geostatic load and surface load.

- Hydraulic design

The hydraulic capacity of the proposed truck tire culvert should be estimated first. The specific method of estimating design discharge, Q_{design}, is left to the designer. The design discharge, which is a storm runoff at a certain frequency, can be determined from the drainage area. Equations and charts that relate the drainage areas and runoffs can be obtained from hydraulic handbooks or the Iowa Department of Transportation. As an example, Figure 2 is a runoff chart for Iowa. The relationship between drainage area and peak rate of runoff shown on this chart is for a storm frequency of 50 years and very hilly land with mixed cover terrain. Factors may be applied for different storm frequencies (called frequency factor – FF) and for different land descriptions and uses (called land use factor – LF).

After the design discharge, Q_{design}, length of the culvert, L, and slope of the culvert, S_o are defined, Figure 3 can be used to determine if the truck tire culvert has enough hydraulic capacity. Figure 3 indicates the relationship between the hydraulic capacity and the length and slope of the truck tire culvert when the tailwater is low. It was established through hydraulic analyses. To use Figure 3, find Q_{design} on the ordinate and draw a horizontal line to the line representing the length of the culvert (interpolate if necessary); from there draw a vertical line and obtain the slope on the abscissa. This slope is the minimum slope required for conducting the design discharge within the maximum water level requirement and is called S_{min}. If the slope of the truck tire culvert is equal or greater than S_{min}, a truck tire culvert can be used for this project.

Figure 3 indicates that for slopes equal to or greater than 0.11, the hydraulic capacity is no longer a function of the length and slope of the culvert. This is because 0.11 is the critical slope at which flow changes from outlet control to inlet control. For the flow with inlet control, the hydraulic capacity of the culvert is independent of the length and slope of the culvert.

- Structural design

Once the hydraulic capacity of truck tire culvert is found to be adequate for the project, the next step is structural analysis. This analysis is to assure that the maximum pipe deflection of the culvert is less than 5% of the outside diameter after the culvert is put into use.

As indicated before, the recommended minimum and maximum soil covers of a truck tire culvert for three soils at different degrees of compaction are shown in Tables 2 and Table 3. Table 2 can be used to determine the minimum soil cover and Table 3 can be used to determine the maximum soil cover over the truck tire culvert. As indicated on the flowchart, if the soil cover at the proposed compactive effort falls between the minimum and maximum values, a truck tire culvert can be used.

If both the hydraulic and structural criteria are met during the design process, then construction of the truck tire culvert may proceed.

Table 1. Soil type information for CANDE analyses

Unified classification	Degree of compaction (standard AASHTO)	Total unit weight γ_m (kN/m^3)	Initial friction angle Φ_o (degree)	Reduction in friction angle for a 10-fold increase in confining pressure $\Delta\Phi$ (degree)	Cohesion intercept C (kN/m^2)	Modulus number K	Modulus exponent n	Failure ratio R_f	Bulk modulus number K_b	Bulk modulus exponent m
Silty clay (CL)	45	9.7	23	11	0	16	0.95	0.75	15	1.02
	85	18.9	30	0	4.8	60	0.45	0.7	50	0.2
	95	20.4	15	4	62.0	120	0.45	1.0	80	0.2
	100	21.2	30	0	19.3	150	0.45	0.7	140	0.2
Silty clayey sand (SM-SC)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	33	0	9.7	100	0.6	0.7	50	0.5
	95	20.4	33	0	20.7	250	0.6	0.7	125	0.5
	100	21.2	33	0	24.1	400	0.6	0.7	200	0.5
Silty sand (SM)	45	11.0	23	0	0	16	0.95	0.55	15	0.94
	85	18.9	30	2	0	150	0.25	0.7	150	0
	95	20.4	34	6	0	450	0.25	0.7	350	0
	100	21.2	36	8	0	600	0.25	0.7	450	0

Table 2. Recommended minimum soil covers under H15-truck load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	1.2	0.6	0.6	0.6	0.5	0.5	0.3
Sides are poorly compacted (45%)	1.2	1.2	0.9	0.9	0.9	0.9	0.9

Table 3. Recommended maximum soil covers under geostatic load (m)

Soil type	Silty clay (CL)			Silty clayey sand (SM-SC)		Silty sand (SM)	
Degree of compaction (AASHTO T-99)	45%	85%	95%	85%	95%	85%	95%
Sides are well compacted	13	19	18.5	22	26	41.5	47.5
Sides are poorly compacted (45%)	13	4.5	5.5	6	7.5	10.5	16

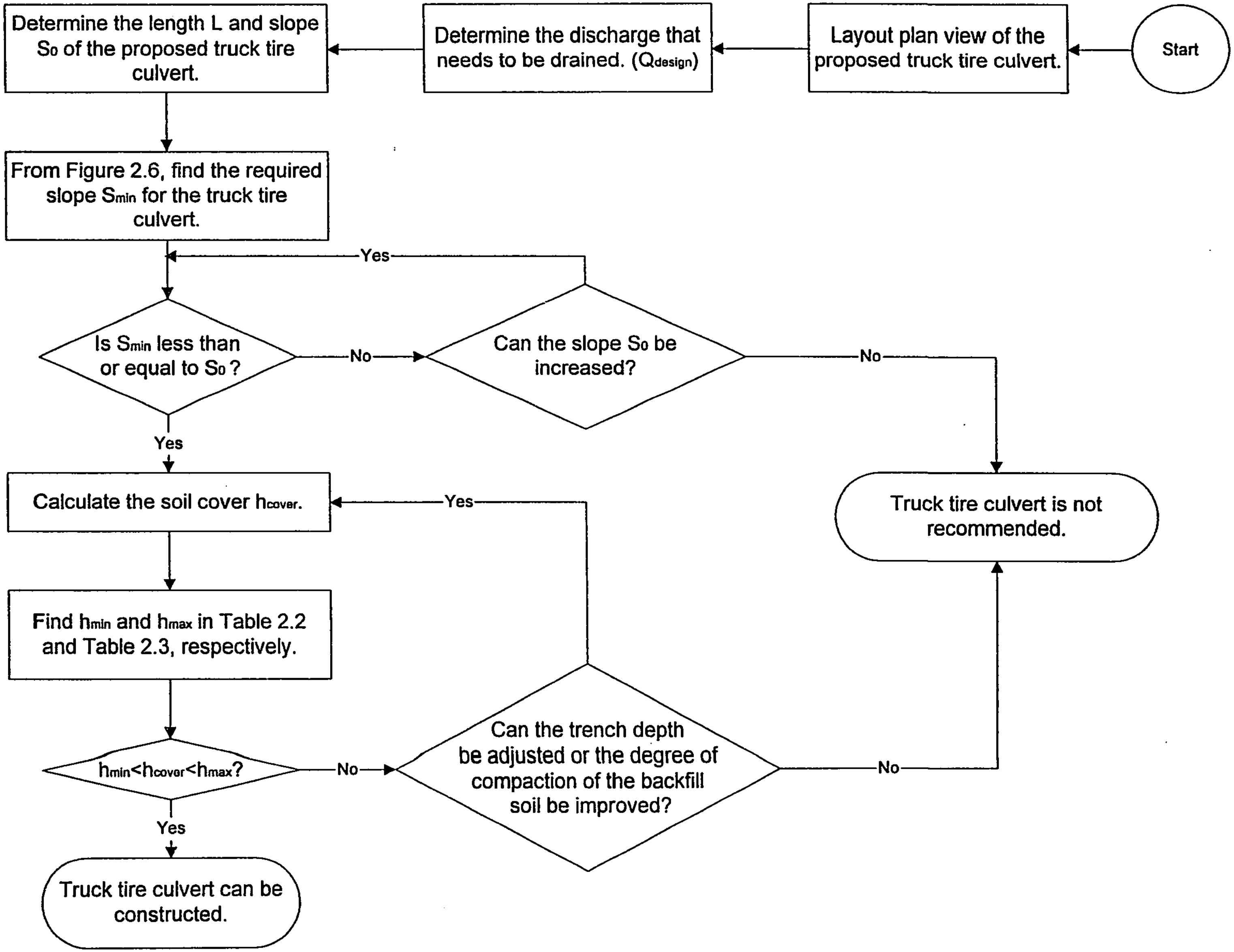

Figure 1. Design flow chart for truck tire culvert

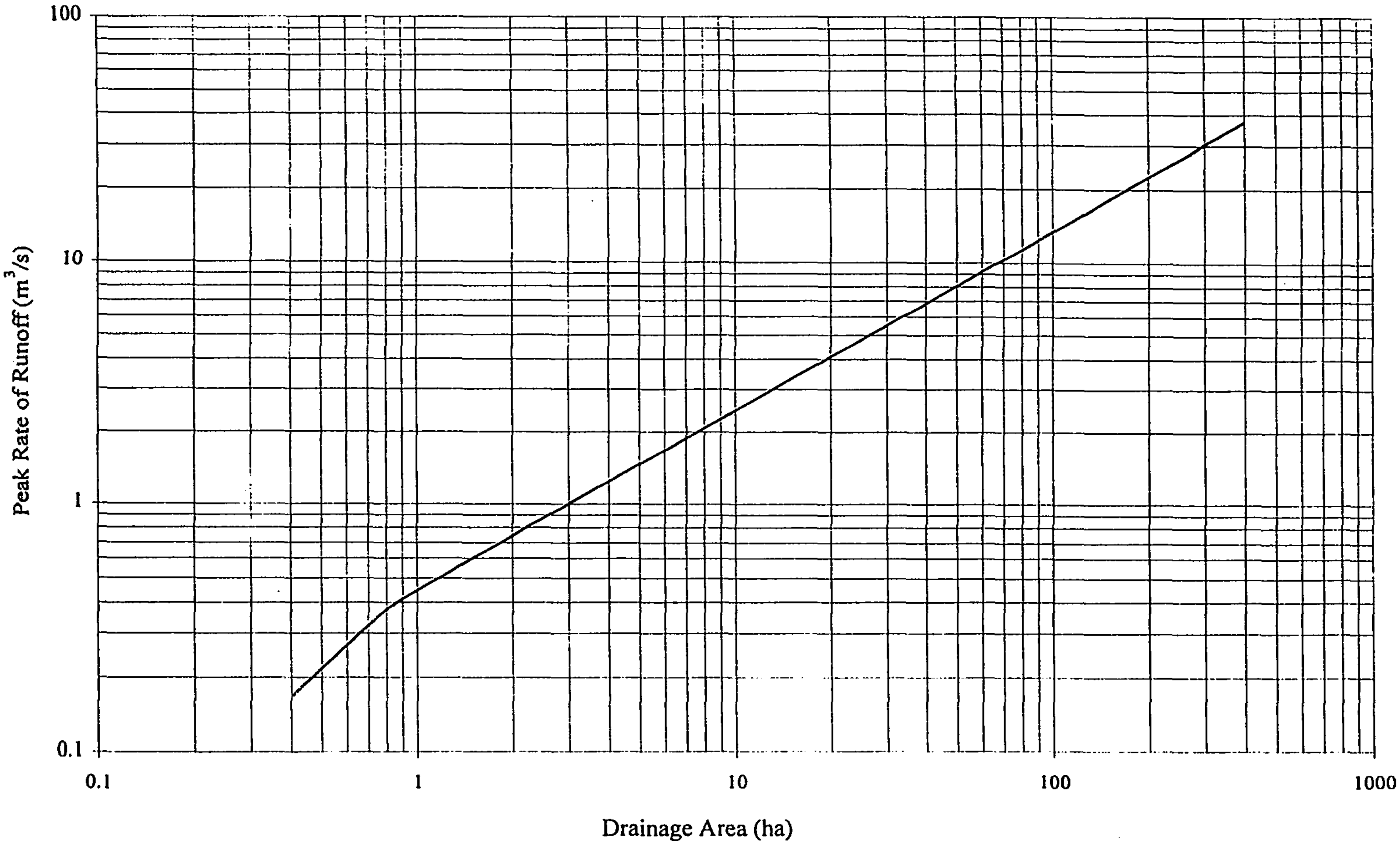

Figure 2. Iowa runoff chart (Frequency of 50 years, mixed cover on very hilly slope)

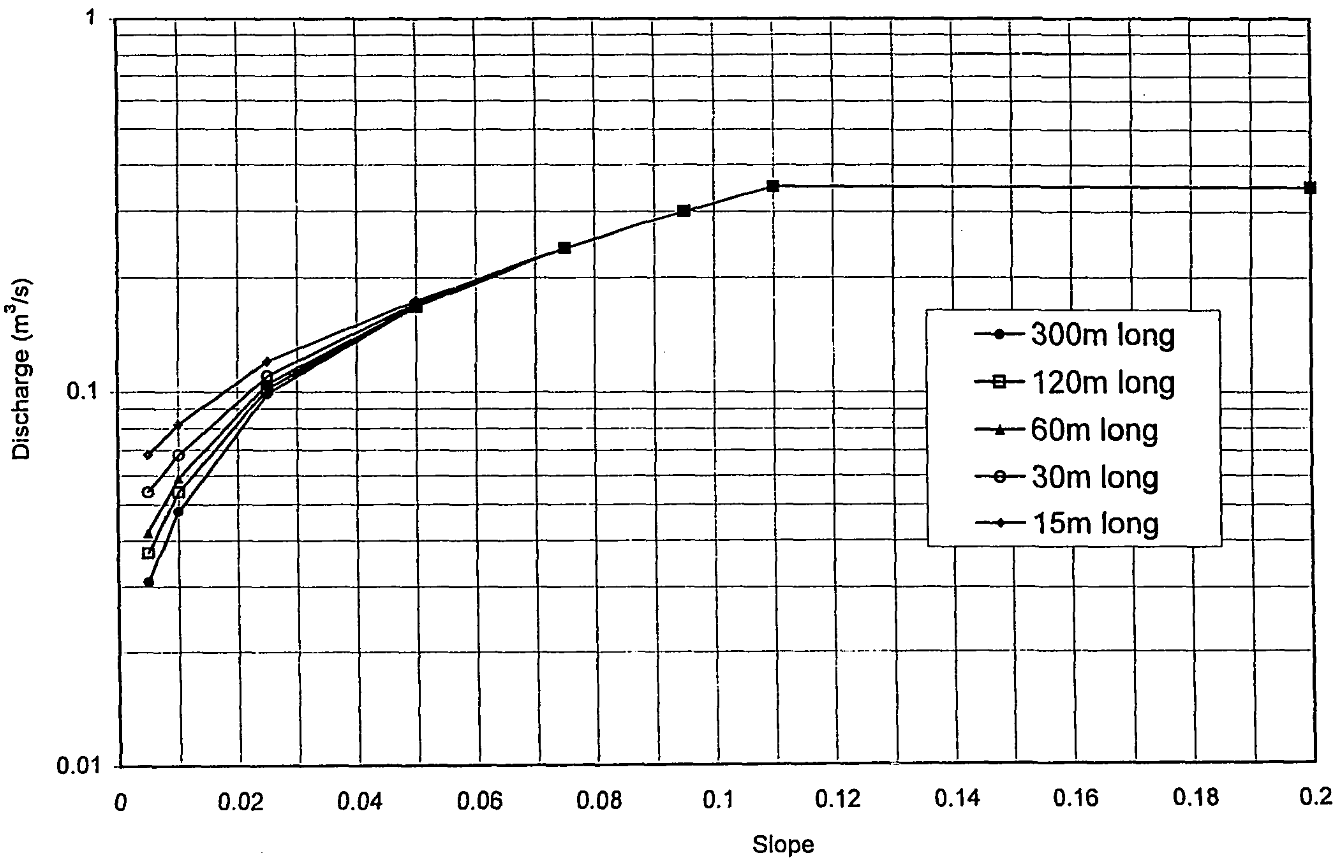

Figure 3. Hydraulic capacity of truck tire culvert (tailwater depth less than 0.2d)

BIOGRAPHICAL SKETCH

Shiping Yang was born on September 10, 1967 in Kaixian, Sichuan, China. He received the Bachelor of Engineering in Hydraulic and Hydropower Construction Engineering from Tsinghua University, China in 1990. He worked as a full-time teaching and research assistant at the Hydraulic and Hydropower Engineering Department of Tsinghua University from 1990 to 1994. He came to the United States to pursue graduate degrees in August 1994 and received the Master of Science in Civil Engineering from the University of Missouri, Columbia in 1996. He enrolled for Ph. D. program in Civil Engineering at Iowa State University in the summer of 1996. He was awarded "Triple-Honor" Student of the Year in 1986 and the Jiang Nanxiang Scholarship in 1989 while he was studying in Tsinghua University.