Design Method For A Flexible Pavement With Rubber Tire Chips In Subgrade

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Abstract

Design Method For A Flexible Pavement With Rubber Tire Chips In Subgrade

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This these proposes a design method using shredded rubber tire chips (RTCs) in the subgrade of a flexible pavement structure.

Discarded automobile tires accumulate in huge quantities every year. RTCs are useful if they are recycled and used in pavement construction.

RTCs are highly compressible producing both elastic and plastic deformation under loading. If sand is mixed they become stronger showing less deformation.

The design method consists of two phases. The first phase deals with the determination of vertical compressive strain (ε_c) at the top of the subgrade and horizontal tensile strain (ε_t) at the bottom of the pavement layer. ε_c and ε_t are determined by Odemark-Boussinesq method. Strain contour charts are prepared for different values of ε_c obtained from various combinations of loads and a wide range of E-values of RTC-sand mixtures. These charts form the basis for determining the thicknesses of the layers above subgrade. Similarly, the values of ε_t obtained for different combinations of pavement and base and the standard axle load of 18 kips

(80 KN) are placed in a graph which is used for determining the thickness of pavement layer.

In the second phase, a design method is developed integrat-ing the above procedures. The design method determines the depth at which the RTC-sand layer is to be located below the top of the pavement.

A set of computer programs are developed for determining ε_c and ε_t using Odemark-Boussinesq method.

This thesis is organized in chapters to report the results of the research work in an orderly manner.

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List of Symbols

A/C	asphalt concrete
a	radius of loaded area
β	material constant indicating the increase in elastic modulus per unit increase in stress invariant
C_f	correction factor
d	deflection
d_0	surface deflection at the centre of loaded area
d_x	surface deflection at a distance r_x
d_z	deflection at a depth z below ground surface
E	elastic modulus (Young's modulus)
E_0	initial elastic modulus or the modulus when the stress invariant is zero
E_p	pavement modulus
E_{sg}	subgrade modulus
E_1, E_2, E_3, E_4	pavement modulus, base modulus, subbase modulus and subgrade modulus respectively
ε	strain (ε_{ij})
ε_c	vertical compressive strain
ε_r	resilient or recoverable strain
ε_t	horizontal tensile strain
τ	shear stress
τ_{xz}	xz shear stress
f_L	load equivalency factor

h_1, h_2, h_3	thickness of pavement, base and subbase layer
h_e	equivalent thickness
K_1, K_2	experimentally determined material constant
K_0	coefficient of earth pressure at rest
M_c	constrained modulus
M_R	resilient modulus
MET	method of equivalent thickness
N	number of load repetitions to failure
N_v	number of vehicles in each weight class
N_Y	load repetitions per year
θ	stress invariant
σ	stress
σ_d	deviator stress
$\sigma_z, \sigma_r, \sigma_t$	vertical, radial and tangential stress respectively
γ	unit weight
μ	poisson's ratio
P	superimposed load
p	serviceability index
rx	radial distance at x
R_c	radius of curvature of the plane where strain is to be determined
RTC	rubber tire chip
S	design life of pavement
SN	structural number
Z	distance below ground surface

SI Units

The results presented in this thesis are in Imperial Units (foot-pound). Therefore, SI Units are given in parentheses. The following conversions are used:

1 in	=	0.0254 m
1000 lb (1K) force	=	4.48 KN
1 psi	=	6.895 KPa
1000 psi	=	6.895 MPa
1 psf	=	47.88 Pa
1 pcf	=	157.1 N/m^3
1 $lb\text{-}ft/ft^3$	=	4.882 $Kg\text{-}m/m^3$

Chapter 1

Introduction

1.1 Shredded rubber tire chips

Construction of roads across soft and weak soil poses failure threats and economic problems. To reduce the weight of the pavement structure (highway) on such locations wood chips or saw dust have traditionally been used as a replacement for conventional road building materials. But wood products are biodegradable and as such lack durability [19]. On the other hand, rubber tire chips are non-biodegradable and are not subject to rotting (decay) thus more durable and become advantageous over wood chips and sand dusts. Several uses of whole, sliced or chipped tires in different construction projects have been proposed. In most of these applications, tire chips would serve to replace or increase regular or lightweight fill material, as in embankments, for subgrade road beds, for slope stabilization, or as backfill behind retaining walls and bridge abutments.

At present 75-80% of scrap tires are buried in landfills which is not only wasteful but also costly. Disposal of whole tires has been banned in the majority of landfill operations because of the bulkiness of the tires and their tendency to float to the surface with time due to buoyant action arising from emitting gases. As such, waste tires should be shredded into pieces before they are put into the landfills [7].

1.2 Flexible pavement structure

The flexible pavement structure is a four layer system consisting of an asphalt wearing surface (pavement), a granular base, a sandy subbase and a subgrade of rubber tire chips (RTCs) and sand, hereafter called RTC-sand mixture which for the design purpose is assumed to extend to an infinite depth. Traffic loads are subjected to the road surface and are transmitted through the four layers stated above until they are supported by the native soil foundation. The axle load from the vehicular traffic is distributed on the asphalt concrete wearing surface as a contact pressure from the wheels. This stress is then distributed through the asphalt, base, subbase and finally through the subgrade(R.T.C-sand layer). The superimposed load is distributed over a larger area as the depth increases. The contact pressure is directly proportional to the axle loads which in other words means that the magnitude of contact pressure increases as the axle load increases on the pavement surface. Therefore, the magnitude of stress developed on the surface of the RTC-sand layer varies with the magnitude of axle loads and the depth of A/C layer,base and subbase layer.

The stresses, and strains in the RTC-sand layer, (subgrade) are dependent on the pressure applied at the top of the RTC-sand layer which in turr are dependent on the pressure applied on the pavement surface. The magnitude of strains produced on the top of RTC-sand layer is thus a function of stress and material behaviour.

The stresses, strains and deflections produced on the top of RTC-sand layer due to traffic wheel load are determined by Boussinesq's equation after converting all the layers to an equivalent depth of uniform mass by Odemark's method. The vertical compressive strains produced on the top of RTC-sand (subgrade) layer and the horizontal tensile strains produced at the bottom of asphalt wearing course (pavement) are considered critical values for designing the flexible pavement system by Asphalt Institute method.

1.3 Objective of the study

The main objective of this study is to find out a design method for a four layer pavement system comprising of asphalt wearing course (pavement), base, subbase and a RTC-sand layer (subgrade) resting over natural soil. The fourth layer (subgrade) is made up of rubber tire chips mixed with locally available sand because the tire chips alone can not withstand even moderate loading and exhibit numerous practical problems during field compaction and construction. Tire chips are obtained by shredding scrap tires and are chosen for the following reasons.

a. Used and discarded tires can be recycled in order to facilitate their easy disposal. As tires occupy a large landfill space, disposal of large quantities of tires accordingly has many economic and environmental implications.

b. Waste shredded tires are useful as a light fill material in road embankments thus reducing their construction costs.

c. Scrap tire piles, which are growing each year, pose two significant threats to the public: fire hazards (once set ablaze they are extremely difficult to extinguish), and health hazard (the water held by the tires provides as an ideal breeding ground for mosquitoes).

Beyond the main objective, the study is also aimed at establishing the followings:

1. To develop strain contour charts based on different wheel loads and equivalent thicknesses of all layers above the subgrade. Each chart will be for a specific subgrade material (RTC-sand mixture) with distinct properties.

2. To develop a series of strain contour charts based on a range of subgrade modulus values and equivalent thicknesses of all layers above the subgrade.

3. To develop curves based on actual pavement thicknesses and horizontal tensile strains.

1.4 Structure of thesis

Chapter 2 of this thesis outlines the literature review describing different methods of flexible pavement analysis including the Odemark-Boussinesq method applicable in geomechanics and highway engineering. It also states various properties which will be required for the study.

Chapter 3 describes the theoretical background and the assumptions made for the analysis of the pavement system.

Chapter 4 deals with the material properties of shredded rubber tire chips and describes the procedures for obtaining data from laboratory tests and field observations which will be required for subsequent use in the design.

Chapter 5 shows the pavement model and arranges the results of the analysis in matrix form. It also shows the methodology for obtaining different strain contour charts based on material properties used in the pavement, base and subgrade.

Chapter 6 explains how different strain contour charts are used for the purpose of obtaining equivalent thickness and subsequently different layer thicknesses and shows a design example.

Chapter 7 illustrates the computer program which has been developed for this study. The flowchart and program instructions on its use are also described.

Chapter 8 outlines the conclusions of this study and provides suggestions for further research.

Appendix-A shows detailed calculation of surface deflections by Odemark-Boussinesq method (linear elastic) and by iterative method of successive approximations (nonlinear elastic).

Appendix-B contains Tables of strain values and strain-contour charts.

Appendix-C exhibits the print out of computer program developed for this study.

Appendix-D shows the sample printouts of results.

Chapter 2

Literature Review

2.1 Introduction

Pavement design basically deals with measuring the strength of the pavement surfacing and the underlying individual layers including determining the thickness of the pavement wearing surface, base, sub-base, subgrade and other layers, if any, which ultimately rest on the native soil.

Flexible pavements are layered systems with stronger materials placed on top where the intensity of stress is greater and weaker materials at the bottom where the intensity is low. Following-up this design principle results in utilising local materials with most economic design.

Wheel loads of vehicular traffic are applied to the pavement structure which may number several millions over it's life time. When a load passes over the pavement, some deflection of the surface and the underlying layers takes place. If the load is excessive or the supporting layers are weak to withstand the load, the load repetitions will cause roughening and cracking which ultimately will result in the complete failure. This deflection may occur from elastic deformation of paving materials, from consolidation of underlying layers or from combination of elastic and plastic deformation.

Elastic deformation is caused when the wheel load temporarily deforms the foundation materials and compresses the air that fills the voids of the base and underlying layers. But in truly elastic deflection, the pavement surface will return back to its original position as soon as the load is removed or withdrawn so that pavement deformation does not occur even under the repetitive load applications. On the other hand, pavement deformation takes place when the load produces excessive stresses in the pavement structure causing either densification of the material or producing shear deformation (plastic flow with no volume change). However, permanent deformation due to plastic flow is beyond the scope of this study, but for further information on this, Desai and Siriwardane maybe referred to [4].

2.2 Layered theory

As early as 1943, Burmister came out with a method for determining the stresses and displacements in a two layer system [9]. Before this, however, Boussinesq, a French engineer and mathematician in 1883 formulated a set of equations for calculating the stresses, strains, and deflections of a homogeneous, isotropic, linear-elastic half space under a point load which were later integrated to obtain those due to a circular loaded area [18]. Based on Burmister's method, Acum and Fox presented exact solutions for the boundary stresses in the center line of a circular uniformly distributed load acting on the surface of a three-layer half space [9]. Since then a large number of computer programs have been developed for calculating stresses, strains and deflections on layered elastic systems. Some of the more widely used are the programs developed by Shell (BISTRO and BISAR) and by CHEVRON (ELSYM 5). A number of finite element programs which can include non-linear elastic materials such as KENLAYER, MICHPAVE, ILLI-PAVE etc. have also been developed.

Odemark, however, presented the method of equivalent thickness (MET) which states that a system consisting of layers with different moduli is converted into an equivalent system where all layers have the same modulus and on which Boussinesq's equations maybe used [18].

Per Ullidtz shows that the pavement responses (stresses, strains and deflections) calculated by the method of equivalent thickness utilising Boussinesq's equations are comparable to the responses calculated for the same structure of loading with the CHEVRON computer program [18].

Odemark's method of equivalent thickness, however, has some limitations with respect to its use such as the moduli should be decreasing with depth, preferably by a factor of at least two between consecutive layers and the equivalent thickness of a layer should, preferably, be larger than the radius of the loaded area [18].

2.3 Mechanistic-Empirical methods

The mechanistic-empirical method of pavement design is a basic approach to the mechanics of materials which relates some input, such as a wheel load from traffic, supporting or bearing values of materials and soils etc. to output or pavement response, such as stress, strain and deflection. The response values are used to predict distress based on laboratory test and field performance data.

Dependence on observed performance is necessary because theory alone has not proven sufficient to design pavements realistically [9].

Kerkhoven and Dormon first suggested the use of vertical compressive strain on the surface of subgrade as a failure criterion to reduce permanent deformation, while Saal and Pell recommended the use of horizontal tensile strain at the bottom of the asphalt layer to minimize fatigue cracking [9]. The above concepts for pavement design was first presented in the United States by Dormon and Metcalf [9].

The use of vertical compressive strain to control permanent deformation is based on the fact that plastic strains are proportional to elastic strains in paving materials. Thus, by limiting the elastic strains in the subgrade, the elastic strains in other layers above subgrade will also be controlled. Therefore, the amount of permanent deformation on pavement surface will also be restricted. These two criteria have since been utilised by Shell Petroleum International (Claussen et al.) and the Asphalt Institute (Shook et al.) in their mechanistic-empirical methods of design [9]. The advantages of using this principle of design are the improvement in the reliability of the design, the ability to predict the types of distress and the capacity to extrapolate from the limited field and the laboratory data [9].

2.4 Nonlinear analysis

Granular materials and subgrade soils normally behave nonlinear under loading with an elastic modulus varying with the level of stresses. The elastic modulus which is used for the analysis of layered systems is the resilient modulus and can be obtained from the repeated unconfined or triaxial compression tests. The resilient modulus of granular materials increases with the increase in the magnitude of stress, whereas that of fine-grained soils decreases with the increase in stress intensity . Huang states that if the relationship between the resilient modulus and the state of stresses is given, a method of successive approximations can be used for the analysis of nonlinear homogeneous mass [9]. This has been incorporated in the KENLAYER computer program.

The successive approximations method to analyze a nonlinear halfspace is to divide it into a number of layers and determine stresses at the midheight of each layer by Boussinesq's equations based on linear theory. From the stresses thus obtained, the elastic modulus E for each layer is determined from the following equation [9]:

$$E=E_0(1+\beta\theta) \tag{2.1}$$

where θ is the stress invariant, or the sum of the three normal stresses; E is the elastic modulus under the given stress invariant; E_0 is the initial elastic modulus, or the modulus when the stress invariant is zero; and β is a soil constant indicating the increase in elastic modulus per unit increase in stress invariant. The stress invariant should include the effect of the applied load and also the geostatic stress which can be expressed as [9]:

$$\theta = \sigma_z + \sigma_r + \sigma_t + \gamma z(1+2K_0) \qquad (2.2)$$

where σ_z, σ_r, σ_t are the vertical, radial and tangential stress due to superimposed loading; γ is the unit weight of the material; z is the distance below ground surface at which the stress invariant is computed, K_0 is the coefficient of earth pressure at rest.

The deformation of each layer which is the difference in deflection between the top and bottom of each layer based on the given E, can then be obtained. Starting from the depth far below from the surface where the vertical displacement may be assumed zero, the deformations are added to obtain the defections at various depth. The assumption of Boussinesq's stress distribution was used by Vesic and Domaschuk to predict the shape of deflection basins on highway pavements and satisfactory agreements were reported [9].

The equation 2.1 is one of the constitutive equations for sands. A general constitutive relationship between resilient modulus and the stress invariant for granular materials may be expressed as:

$$E=K_1\theta^{K2} \tag{2.3}$$

where K_1 and K_2 are experimentally determined constants and θ is the stress invariant. The values of K_1 and K_2 for granular materials are presented in Yang H. Huang [9].

2.5 Determination of layer moduli of flexible pavements

The literature review reveals that the subgrade modulus including the overall pavement modulus can be obtained using load related pavement surface deflection measurements with the help of falling weight deflectometers (FWDs). Noureldin A. Samy uses the concept of back calculation and states that a unique location exists on the pavement surface at a radial distance r_x, from the loading centre that deflects with a value D_x exactly equal to the deflection of a point on the top of the subgrade underneath the loading centre [12]. The theory is based on the two-layer elastic flexible pavement system with the material assuming to be weightless, homogeneous and isotropic.

The subgrade modulus E_{sg} can be obtained from the following relation:

$$E_{sg}=2.149/r_x*D_x \tag{2.4}$$

where E_{sg} is the subgrade modulus in psi, r_x is the radial distance in inch from the loading centre and D_x is the surface deflection in inch at a distance r_x.

The equation (2.4) is based on Boussinesq's deflection equation. This method of determining the subgrade modulus was reported by Ullidtz [18].

The overall pavement modulus E_p can also be determined as following:

$$E_p=[716-(2.149/r_x)]/(D_0-D_x) \qquad (2.5)$$

where E_p is the overall pavement modulus in psi and D_0 is the surface deflection at the centre of the loaded area.

Equation (2.5) is based on Burmister's method of deflection in two-layer system. The equation was reported by Noureldin and Sharaf [12].

2.6 Shredded rubber tire chips

Scrap automobile tires available from stockpiles, dumps and other sources are processed through shredding devices to obtain different sizes of chips. They are regarded as a new kind of material and can be used as a lightweight fill material in the subgrade of road embankments. Rubber tire chips are highly compressible and are not as strong as other usual road construction materials to withstand heavy traffic load. To increase load bearing capacity and stiffness, sand is mixed with RTCs. Stress-strain relationship of RTCs shows that the RTCs exhibit nonlinear elastic behaviour after the first cycle of load application. Therefore, the analysis of highway systems including tire chips or tire chips-sand mixtures can be performed using the elastic theory under traffic loads [5]. In order to evaluate the engineering properties of RTC-sand mixtures, different laboratory tests have been conducted as described in [5]. RTC-sand mixture is used as a subgrade material in the pavement system presented in this thesis. A detailed examination of the properties and tests are given in chapter 4. From this examination, the material properties E and μ-values of the various RTC-sand mixtures have been developed for use in this study.

Chapter 3

Theoretical Background

3.1 Introduction

For analysis of the pavement system under study the following assumptions are made:

a. The material properties of each layer are homogeneous, isotropic and linear elastic with different elastic moduli and Poisson's ratios.

b. The behaviour of the flexible pavement under wheel loads is homogeneous half space which has an infinite large area and an infinite depth with a top plane over which superimposed loads are applied.

c. The materials are weightless and all layers are infinite in lateral direction.

d. Each layer has a finite thickness except the lowest layer (subgrade) which is infinite in thickness.

e. At the interfaces the stresses and displacements are same on either side but for frictionless interface the continuity of shear stress and radial displacement is replaced by zero shear stress at each side of the interface.

3.2 Boussinesq's equations

Boussinesq's equations are based on the assumption that the material that constitutes half space is linear elastic. It is known that subgrade materials are seldom elastic and result in permanent deformation under stationary loads. However, under the repeated applications of moving traffic loads, most of the deformations are recoverable and can be considered elastic [9].

The original Boussinesq's theory was based on a concentrated load applied on an elastic half-space. The equations found out by Boussinesq for calculating the stresses, strains and deflections of a homogenous, isotropic, linear elastic semi-infinite space (area and depth) under a point load when integrated result in the determination of the stresses, strains and deflections under a circular loaded area. Fig.3.1 shows a homogenous halfspace subjected to a circular load with a radius " a" and a contact pressure σ_o. The halfspace has an elastic modulus E and a Poisson's ratio μ. A small radial element with centre at a distance " z " below the surface and " r " from the axis of the symmetry as shown in the figure, due to axisymmetry, has three normal stresses $\sigma_z, \sigma_r, \sigma_t$, and one shear stress τ_{rz} which is equal to τ_{zr}. It may be noted that these three stresses are functions of the contact pressure σ_o, vertical depth " z " and the radial distance r from the axis of symmetry.

Boussinesq's equations for determining vertical stresses (σ_z), radial stresses (σ_r), tangential stresses (σ_t), vertical compressive strains (ε_z), horizontal tensile strains (ε_t) and deflections (d_z) at a distance z below the road surface are given as follows [9][18]:

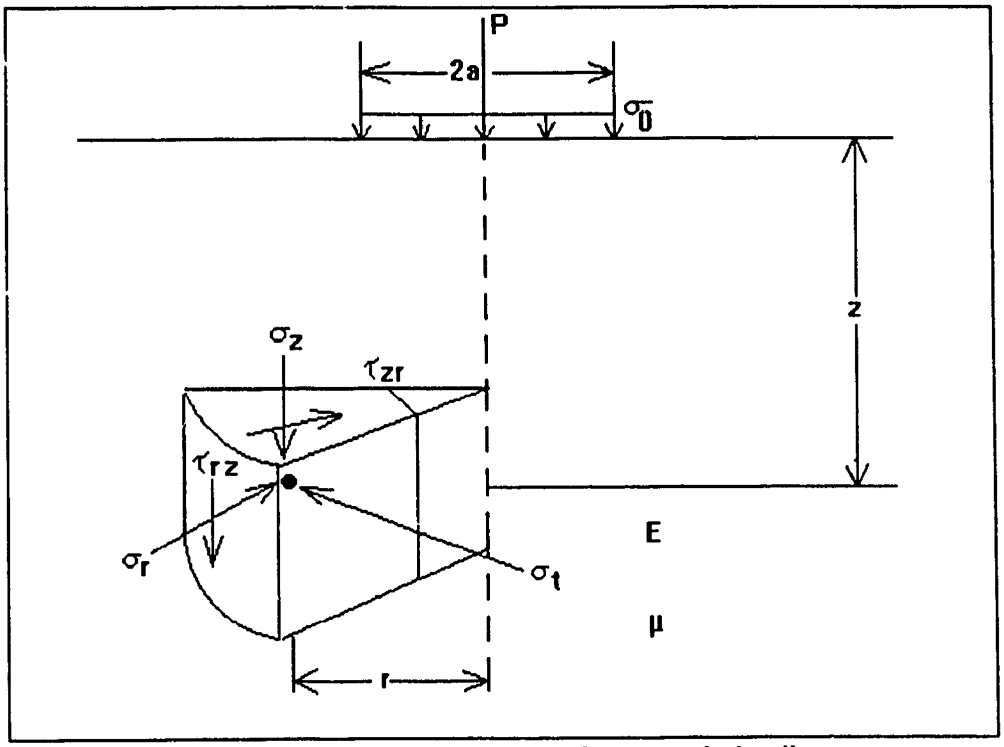


Figure 3.1: Component of stresses under axisymmetric loading.

$$\sigma_z = \sigma_o * \{1-1/[1+(a/z)^2]^{1.5}\} = \sigma_0[1-\{z^3/(a^2+z^2)^{1.5}\}] \quad (3.1)$$

$$\sigma_r = \sigma_t = \sigma_0/2[1+2\mu-2(1+\mu)z/(a^2+z^2)^{0.5} + z^3/(a^2+z^2)^{1.5}] \quad (3.2)$$

$$\varepsilon_z = [(1+\mu)\sigma_o/E]*\{(z/a)/[1+(z/a)^2]^{1.5} - (1-2\mu)\{(z/a)/[1+(z/a)^2]^{0.5}-1\} \quad (3.3)$$

$$d_z = (1+\mu)\sigma_o*a/E*\{1/[1+(z/a)^2]^{0.5} + (1-2\mu)\{[1+(z/a)^2]^{0.5}-(z/a)\} \quad (3.4)$$

$$a = (P/\sigma_o*\pi)^{1/2}$$

where a= radius of the loaded area

σ_o = contact pressure on road surface

P = wheel load in pounds

The horizontal tensile strain may be calculated from the above values and is given by :

$$\varepsilon_r = \varepsilon_t = [(1-\mu)/(2\mu)*\{\sigma_z-E*\varepsilon_z\}-\mu*\sigma_z]/E \quad (3.5)$$

Horizontal tensile strain may also be determined by calculating the radius of curvature, R_c, of the plane, where the strain is to be determined, from:

$$\varepsilon_t = z/2*R_c \quad (3.6)$$

and $$R_c = E*a/[(1-\mu^2)/\sigma_o]/\{1+[1+3/2/(1-\mu)] *(z/a)^2\}*[1+(z/a)^2]^{2.5} \quad (3.7)$$

where, E=modulus of the layer under the pavement layer

and z=distance at which strain is to be determined.

3.3 Odemark's method

Odemark's method is based on the principle of converting a layered pavement system with different moduli into an equivalent system where all layers will have the same modulus and on which Boussinesq's equation may be applied. This method is also known as method of equivalent thickness or in short called MET [18].

For a two layer system, the transformation to an equivalent system is shown in Fig: 3.2.

For calculating stresses, strains and deflections at or below the interface, the layer above the interface is converted into an equivalent layer with modulus E_2 and Poisson's ratio μ_2, but with the same stiffness as the original layer.

In order that the stiffness in both layers remains the same, the term

$$[E*I/(1-\mu^2)]$$

must remain constant, where I is the moment of inertia.

Thus, $$h_e^3*E_2/(1-\mu_2^2) = h_1^3*E_1/(1-\mu_1^2)$$

or, $$h_e=h_1*[\ E_1/E_2*(1-\mu_2^2)/(1-\mu_1^2)\ ]^{(1/3)} \qquad (3.8)$$

where h_e=equivalent thickness.

As Odemark's method of equivalent thickness is not the most accurate method for design of pavement, a correction factor C_f is often introduced in order to obtain a better agreement with the exact elastic theory. In many practical cases, Poisson's ratios of different pavement materials are not well known and as such maybe assumed to be the same value for all materials [18].

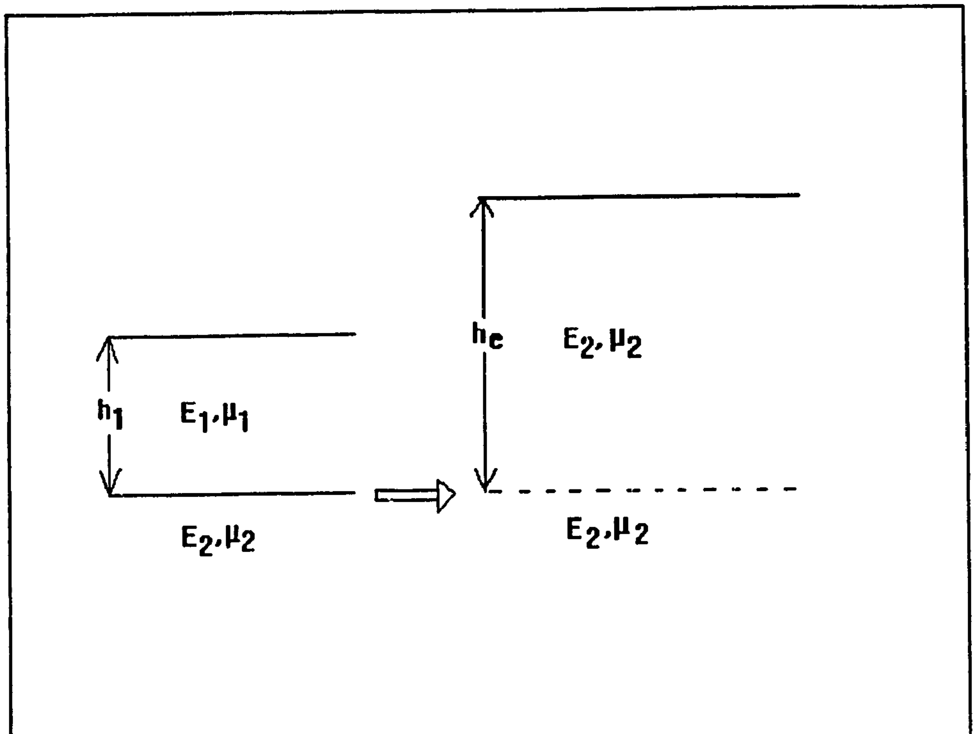


Figure 3.2: Transformations used in Odemark's method.

Hence equation 3.8 becomes

$$h_e=C_f*h_1*(E_1/E_2)^{(1/3)} \quad (3.9)$$

for $\mu_1=\mu_2$.

3.4 Correction factor, C_f

In order to obtain a better agreement with exact elastic theory a correction factor, C_f, is often introduced in Odemark's method. The correction factor, C_f depends on the layer thicknesses, the modular ratios, Poisson's ratios and the number of layers in the pavement structure. But frequently used values are 0.9 for a two layer system and 0.8 for a multilayer system, except for the first interface where it is considered as 1.0 [18].

For the horizontal tensile strain at the bottom of bound layer.

$$C_f=0.96+0.83*a/h_1*E_2/E_1 \text{ for } h_1/a*E_1/E_2 < 10 \quad (3.10)$$

and,

$$C_f=1.13-0.0565*\ln((h_1/a)^2*E_1/E_2) \text{ for } h_1/a*E_1/E_2 > 10 \quad (3.11)$$

Per Ullidtz [18] compared the pavement responses (stress, strain, deflection etc.) utilising Odemark's method of equivalent thickness and Boussinesq's equations with those determined by the Chevron computer program and observed negligible difference which may establish the correctness and genuinity of the MET on which Boussinesq's equations are applied for the determination of the responses in layered pavement structures.

3.5 Asphalt Institute Equations

Asphalt Institute developed design equations on the basis of the laws of mechanics to predict critical strains on pavement structures. In this method, the materials of each layer are characterized by their modulus of elasticity and Poisson's ratio. Traffic load is expressed in terms of an 18 kips (80 KN) single-axle load applied to a pavement on two sets of dual tires [13]. Two strains are considered critical for the design purpose. ε_t is the critical horizontal tensile strain produced at the bottom of first layer due to traffic load and corresponding to the total load repetitions (N). It causes fatigue failure or surface cracking. ε_c is the critical vertical compressive strain on the top of subgrade. It causes permanent deformation or rut on the pavement due to traffic load and corresponding to the total load repetitions (N).

The Asphalt Institute Equations are given by:

$$\varepsilon_t=(N/18.4(c)*4.32*10^{-3}*E^{-0.854})^{-1/3.29} \quad (3.12)$$

$$\varepsilon_c=(N/1.36*10^{-9})^{-1/4.48} \quad (3.13)$$

where ε_t = horizontal tensile strain corresponding to N

N= total load repetitions for the pavement life (No. of EAL in the design life of the pavement)

c= a constant depending on asphalt temperature and void ratio and is considered 1 (for spring).

E= modulus of pavement layer and

ε_c= vertical compressive strain corresponding to N.

Although Boussinesq's equations are concerned with static load, it may be assumed that when a moving axle load acts on the pavement surface it is considered as a static load of momentary duration. As such, the stresses, strains and deflections (pavement responses) can be determined by using Odemark's method of equivalent thickness and using Boussinesq's equation.

Since the traffic loads are repetitive, the material under the load fails after certain number of load repetitions. Thus, two types of failure generally occurs:

i. If the horizontal tensile strain (ε_t) at the bottom of asphalt concrete wearing surface is critical, fatigue cracking on the pavement surface will occur.

ii. If the vertical compressive strain (ε_c) on the top of subgrade is critical, permanent deformation or rutting on the pavement surface will develop.

In this study it is assumed that the vertical strain produced under a momentary load is of the same magnitude as under the repetitive load of the same amount to failure.

3.6 Behaviour of rubber tire chips

Shredded rubber tire chips are light weight materials. They may be used in the subgrade where settlements of embankments due to dead load have to be reduced in order to decrease the overburden stresses on weak and soft soils. These materials are advantageous to other traditionally light weight fill materials such as wood chips etc. because they are not biodegradable and are available almost free of cost with minimal transportation and shredding charge. As the modulus of elasticity of RTCs are very low than that of conventional subgrade soil (5 to 20 times less), they are mixed with locally available sand in order to strengthen their modulus of elasticity. Besides, RTCs are porous and are useful as drainage material in the subgrade.

The subgrade using RTC and sand-mixture of different proportions is assumed to behave as linear elastic because of the repetitive traffic movement over the pavement. Yang H. Huang [9] states that "Boussinesq's solutions are based on the assumption that the material which constitutes the half-space is linear elastic. It is well known that the subgrade soils are not elastic and result in pavement deformation under stationary loads. However, under the repeated application of moving traffic loads, most of the deformations are recoverable and can be considered elastic".

The stress-strain relationship of RTCs is adequately covered in chapter 4 as a part of material behaviour.

Chapter 4

Materials

4.1 Introduction

Over 230 million scrap tires are generated each year from passenger's cars and trucks in the United States. In addition, about 2 billion waste tires have accumulated in stockpiles or in uncontrolled tire dumps across the country. Millions more are scattered in the woods, deserts and empty lots.

"The U.S Environmental Protection Agency (EPA) estimates that of the 234 million tires scrapped each year, 4 percent are recycled, 9 percent are incinerated for energy recovery and 4 percent are exported. Currently 82 percent are landfilled, stockpiled or illegally dumped. In addition, before disposal, 10 million tires are reused and 37 million are retreaded annually" [16].

In Canada, Ontario alone produces 7 to 8 million scrap tires out of passenger cars and trucks every year. More than 60 percent of these scrap tires are currently deposited in landfills and an additional 10 percent are stockpiled [17].

Rubber tire chip products were tested in the Wisconsin Structures and Materials Laboratory under repetitive loads. The test results were supported by the field investigations and were published in the final report on Development of Engineering Criteria for Shredded Waste tires in Highway Applications which was funded by Wisconsin Department of Transportation and Wisconsin Department of Natural Resources. The material properties of RTC-sand mixtures with different proportions used in this thesis have been taken from the above report.

4.2 Rubber tire chips (RTCs)

Rubber tire chips (RTCs) are obtained by shredding discarded automobile tires available in waste tire stockpiles. The whole tire is put into shredding equipment for producing different sizes of chips.

Most processors use mobile shredding equipment with engine capacity varying from 30 HP to 100 HP. These shredders perform a shearing process instead of the tearing process and make more uniform products with uniform cuts eliminating the partial pulling of the reinforcing wires out of the tire chips. RTCs production rate varies from 100 to 400 tons per hour depending upon the equipment type and the required chip size. Shredding cost of RTCs ranges from approximately US $ 30 to 65 in U.S.A and CDN $ 60 to 80 per ton in Canada; one ton of RTCs requires approximately 100 tires. Usually the chips are of irregular shape and range from sizes of 1x2 in. to 4x8 in. (0.0254 x 0.0508 m to 0.1016 x 0.2032 m) with the most common size chips being 2x3 in (0.0508 x 0.1016 m). The particle size of shredded tires is a function of the number of passes through the shredded device. Minimal processing (one pass) results in large sizes whereas two to four passes through a shredder result in much smaller pieces, whose size can be characterized by the opening size of a sieve [11].

RTCs thus obtained are chosen as a light weight fill material mixed with locally available sand and could be used in the subgrade of the pavement structure which will ultimately rest over native soil foundation. Unlike other top layers which are composed of asphalt concrete pavement, gravel base and sandy subbase, the subgrade layer made up of RTCs and sand mixture is considered a new kind of material whose mechanical properties may not be determined simply by performing standard test procedures available for normal soils and aggregates. As such the existing test procedures for normal road construction materials should be modified and developed to determine the mechanical properties of RTC-sand products.

A locally available sand of glacial outwash in nature which is well-graded with some fines in it has been selected to be mixed with RTCs in order to perform laboratory tests for determining the mechanical properties of RTC-sand mixture. Size distribution data of pure RTC samples and grain size distribution of sand samples are shown in figures 4.1 and 4.2 [5].

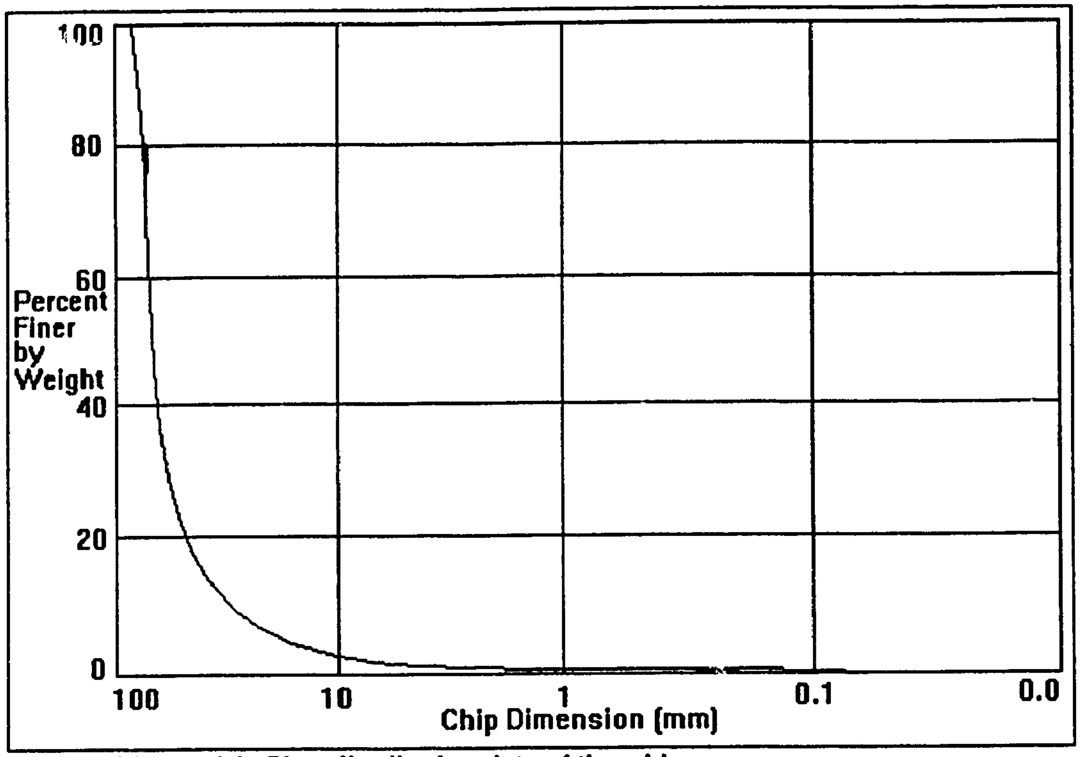


Figure 4.1: Size distribution data of tire chips.

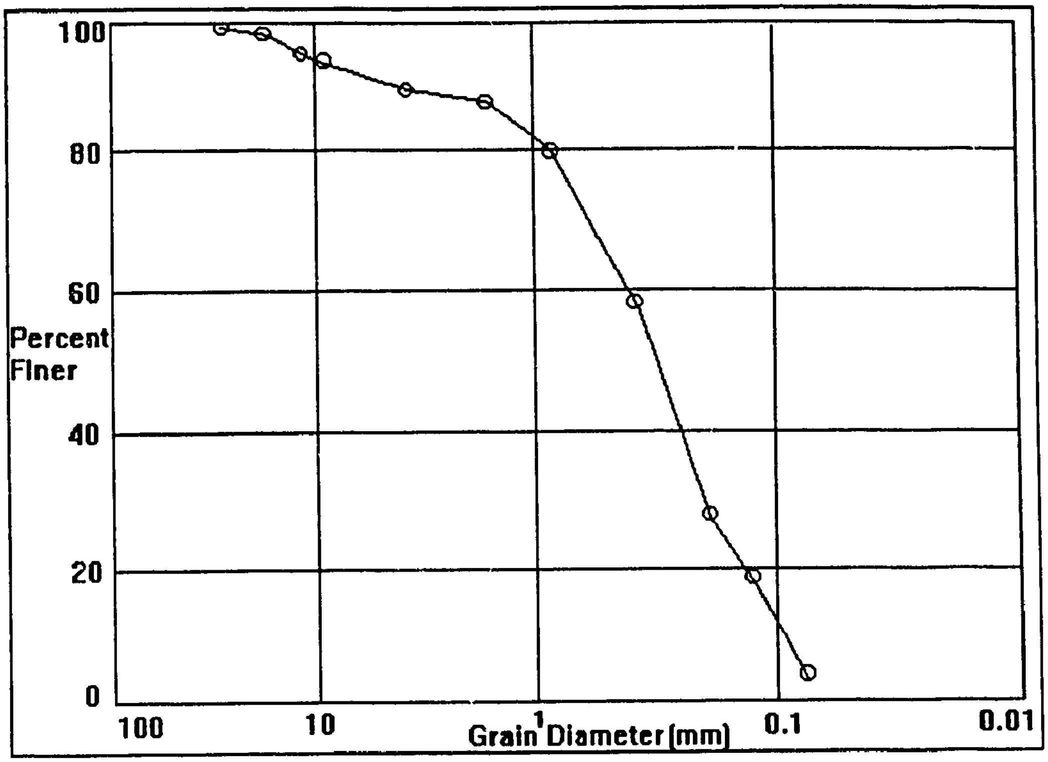


Figure 4.2 : Grain Size Distribution of Sand.

4.3 Engineering properties of tire chips

4.3.1 Compaction characteristics

Shredded tire chips are more flexible and compressible than normal soil particles and hence have a greater capacity to dampen the energy imparted [5]. Besides, as the RTCs are practically of more than 1-in. (0.0254 m) in sizes, the existing compaction test equipments for soils become inappropriate for use of the RTCs. As such a new 12-in. (0.305 m) compaction mold has been made and the compaction hammer has been modified such that the same compactive energy per unit volume is obtained irrespective of the size of the compaction mold . Table 4.1 shows the compaction parameters used in the case of each mold size for the two types of compaction energy-the standard Proctor and modified Proctor energies [5].

Compaction tests on samples of RTCs and outwash sand mixture of four different proportions viz. 30:70, 50:50, 70:30 and 100:0 by weight respectively have been performed using standard Proctor effort. The resulting unit weights are shown in Table 4.2 [5]. It is observed from the table that the unit weight increases with the increasing sand:tire chips ratio.

Table 4.1: Compaction Parameters

Compactive Effort	Mold Size (in)	No. of layers	Wt. of Hammer (lbs)	Hammer Drop (in)	No. of Blows per layer	Compac -tive Energy lb-ft/ ft^3
Standard	6	3	10	12	31	12,400
Standard	12	5	60.4	18	14	12,400
Modified	6	3	10	12	140	56,244
Modified	12	5	60.4	18	64	56,244

(1-in.= 0.0254 m, 1 lb. = 4.48 N, 1 lb-ft/ft^3 = 4.882 Kg-m/m^3)

Table 4.2: Compaction Data

Mold Size (in)	Sand Type	% of RTCs	% of Sand	Unit Weight of Seating Load (pcf)	Porosity of seating Load
6	out-wash	30	70	101.85	0.167
12	"	30	70	102.56	0.162
6	"	50	50	77.69	0.255
12	"	50	50	81.87	0.215
6	"	70	30	46.29	0.490
12	"	70	30	44.38	0.511
6	"	100	0	37.06	0.513
12	"	100	0	34.91	0.541

(1-in.= 0.0254 m, 1 pcf = 157.1 N/m^3)

4.3.2 Compression behaviour

RTCs are highly compressible because of their high porosity and high rubber content. When a load is applied on RTCs, they would compress due to the following reasons:

(a) bending and reorientation of the chips into a more compact and densifying state.

(b) compression of individual chips under stress.

To determine compression behaviour, a series of repetitive constrained compression tests have been performed on both pure RTCs and the mixture of RTC-sand by placing the material in a 6-in. (0.1524 m). Proctor mold and then applying a vertical load using a 60-kip (268 KN) compression machine [5]. A typical load-displacement response of pure RTCs is shown in fig 4.3.

The initial porosity of RTCs which was about 0.67 decreased to a porosity of 0.50 as a result of 2.2 in. (0.0559 m) (about 36%) compression (the sample being 6" (0.1524 m) high) at a vertical load of 2800 lbs. (12.54 KN) corresponding to a lateral pressure of about 100 psi. (690 KPa). Hall (1991) reported about 30% compression under a lateral pressure of 10 psi (69 KPa) for his RTCs of sizes ranging from 0.75 in. (0.019 m) to 1.50 in. (0.038 m). Fig. 4.3 shows that major compression takes place in the first cycle and a portion of this compression is not recoverable in this type of laterally confined test but there is significant rebound when the load is removed. The subsequent cycles, however, show similar load displacement curves with less

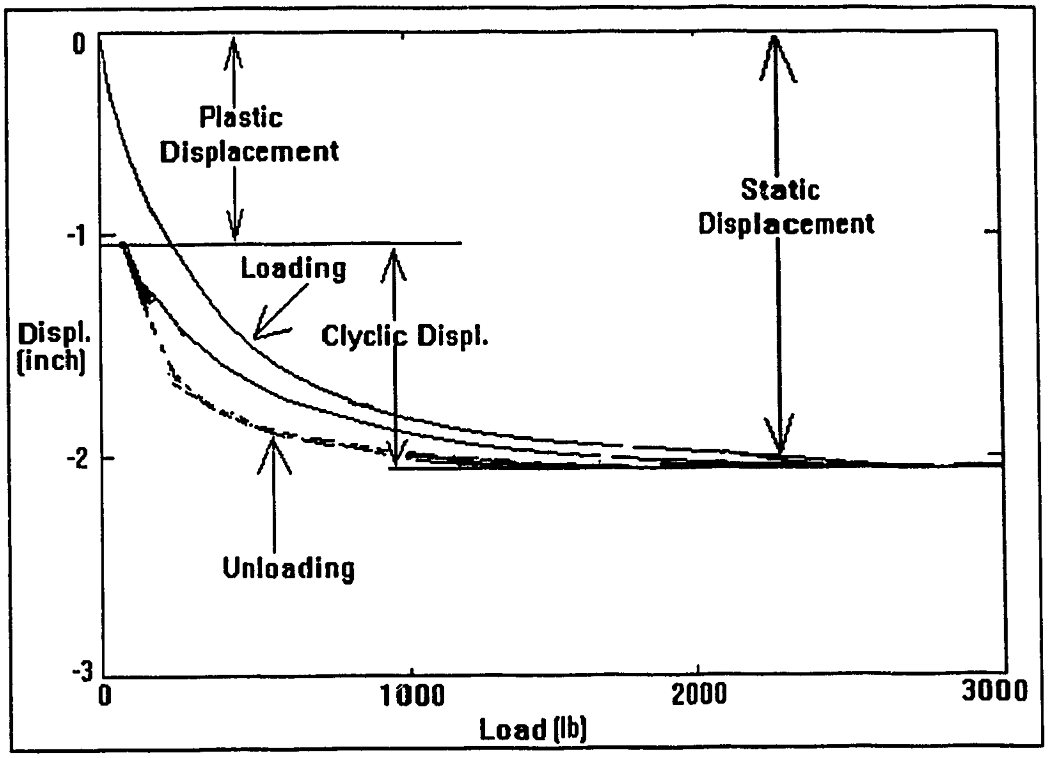


Figure 4.3: Vertical displacement Vs. load response of RTCs.
(1-in. = 0.0254 m, 1 lb. = 4.48 N)

rebound. It is also observed that the slope of rebound/compression curve is considerably lower beyond a vertical load of about 1000 lbs (4.48 KN).

Fig 4.4 represents the typical load-displacement response of sand which shows the displacement of only about 0.3 in. (0.0076 m) (about 5%) compression at a vertical load of 2800 lbs (12.54 KN). This corresponds to about 14% of the compression of pure RTCs at the same load.

Fig 4.5 shows the percent compression Vs. sand content of RTC-sand mixture. It is observed that beyond a sand content of about 40% the compressibility significantly reduces from about 30 to 40% to less than 20%. This is because the sand being finer enters the open voids of the tire-chips mass and reduces the compression [5].

4.3.3 Compression tests

The compacted specimens as described in 4.3.1 were subjected to quasi-static compression in order to determine deformation modulus of deep fill-materials (RTC-sand mixtures) where lateral constraint is approximated in the field. The compression tests were preceded by the application of a small initial seating load to obtain a reference initial specimen height for strain computations since surface of the specimens were not even. The seating load was about 500 psf (23.94 KPa). Subsequent to the application of the seating load, the vertical load was increased to a maximum value and then it was lowered back to the seating load followed by three cycles of

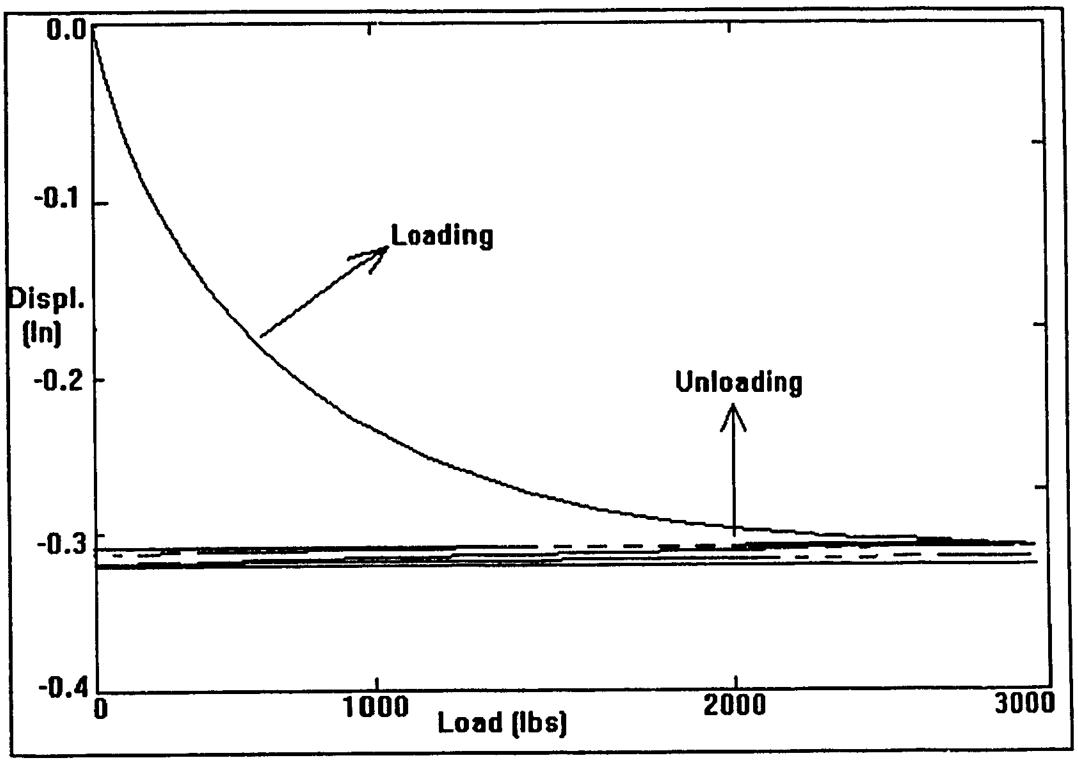


Figure 4.4: Vertical displacement Vs. load response of sand.

(1-in. = 0.0254 m, 1 lb. = 4.48 N)

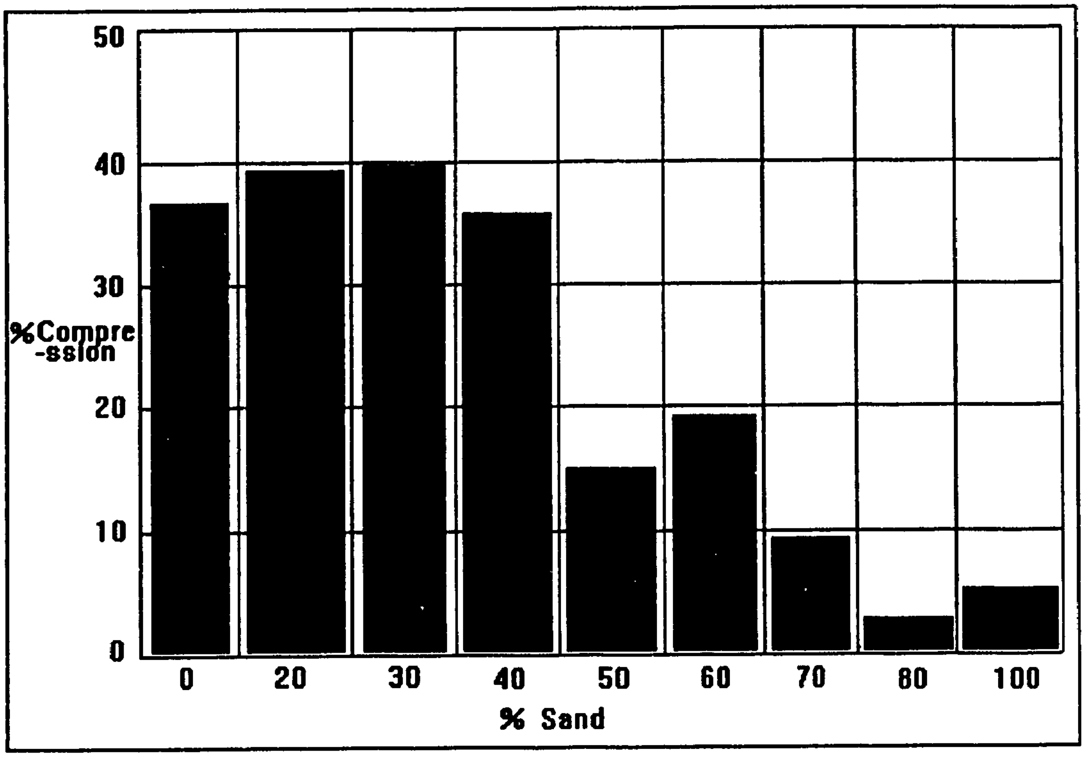


Figure 4.5: Compression Vs. sand content of RTC-sand mixture.

loading/unloading between the seating load and the maximum load. The maximum loads were 4080 psf (0.195 MPa) and 14,000 psf (0.67 MPa) in 12-in. (0.305 m) and 6-in. (0.1524 m) molds respectively [5].

The quasi-static constrained repetitive loading test which resulted in maximum strain obtained at the end of the first cycle of loading (static strain) as well as maximum strain generated in the subsequent cycles of loading (cyclic strain) have been shown in Table 4.3. The constrained modulus (M_c) which is the slope of the cyclic loading portion of the strain-stress plot have been shown in Table 4.3. Both the static strain and cyclic strain decrease with the increase in sand percentage. But the compaction test results described earlier showed increase in unit weights with the increase in sand percentage in the RTC-sand mixtures.

4.3.4 Resilient modulus

Resilient modulus of pavement materials is the elastic modulus under repetitive loading. It is an important material property used in the analysis and design of pavement systems.

It is well known that most paving materials are not elastic but experience some permanent deformation after each load application. However, under repetitive loading, materials undergo certain unrecoverable (plastic) deformations in addition to the recoverable (elastic) deformations. The plastic strains can be determined by monitoring the accumulat-

Table 4.3: Compressibility Data

Mold Size (in)	Sand Type	% of RTCs	% of Sand	Strain Static	Strain Cyclic	Constrained Mod. M_c (psf)
6	out-wash	30	70	0.052	0.029	$3.52*10^5$
12	"	30	70	0.042	0.018	$2.17*10^5$
6	"	50	50	0.107	0.092	$9.01*10^4$
12	"	50	50	0.083	0.066	$5.56*10^4$
6	"	70	30	0.236	0.105	$2.33*10^4$
12	"	70	30	0.267	0.091	$2.73*10^4$
6	"	100	0	0.251	0.121	$2.06*10^4$
12	"	100	0	0.296	0.111	$2.24*10^4$

(1-in = 0.0254 m, 1 psf = 47.88 Pa)

ing unrecovered strains during the cycles of repetitive loading. These permanent strains are indicative of the rut potential in a flexible pavement system. As such, a series of resilient modulus tests were performed on RTC-sand mixtures. But due to excessive sample displacement and distortion, pure RTCs could not be tested [5].

The resilient modulus test is performed to examine the behaviour of the material as a support system for the pavement. When a heavy vehicle passes over a pavement, a dynamic stress pulse is transmitted to the material. This stress causes the material to deform, which in turn allows the pavement to deflect and bend. The stresses and strains developed within the pavement due to the deflection and bending are the factors which control the pavement performance. Thus, the pavement performance is directly influenced by the load-deformation behaviour of the material [8].

The basic concept of the resilient modulus test is to duplicate and measure this behaviour in the laboratory. The test is conducted by placing the sample in a triaxial cell and subjecting it to a confining pressure. The confining pressure is intended to simulate the confinement the material would experience under the pavement. Dynamic load pulses are applied to the material and the resulting deformation or specimen strain is measured. The load pulse durations are typically about 0.1 sec and are intended to simulate the stress pulse in the subgrade caused by the passage of a heavy vehicle [8].

The resilient modulus, M_R is obtained from the load and deformation using the following equation [8]:

$$M_R = \sigma_d/\varepsilon_r \qquad (4.1)$$

where, σ_d is the stress caused by the dynamic load pulse also known as the deviator stress and ε_r is the resilient or recoverable strain.

The idealization of the RTC-sand mixtures as linear elastic materials after a number of initial load cycles, defined by two parameters: Young's modulus, E and Poisson's ratio, μ are shown in figure 4.6 [5].

The relationship of Young's modulus, E to the constrained modulus, Mc is given by the following equation [5]:

$$E=[(1-2\mu)(1+\mu)*M_c]/(1-\mu) \qquad (4.2)$$

This relationship was used along with the measured values of the constrained modulus, M_c obtained earlier from the quasi-static constrained repetitive loading tests shown in table 4.3 and Poisson's ratio of 0.2 (based on the uniaxial compression tests) in calculating the elastic modulus, E of RTC-sand mixtures for subsequent analysis and design of the flexible pavement system.

Following is an example showing the calculation of modulus of elasticity, E of RTC-sand mixture from the constrained modulus, M_c obtained from laboratory test as shown earlier in Table 4.3

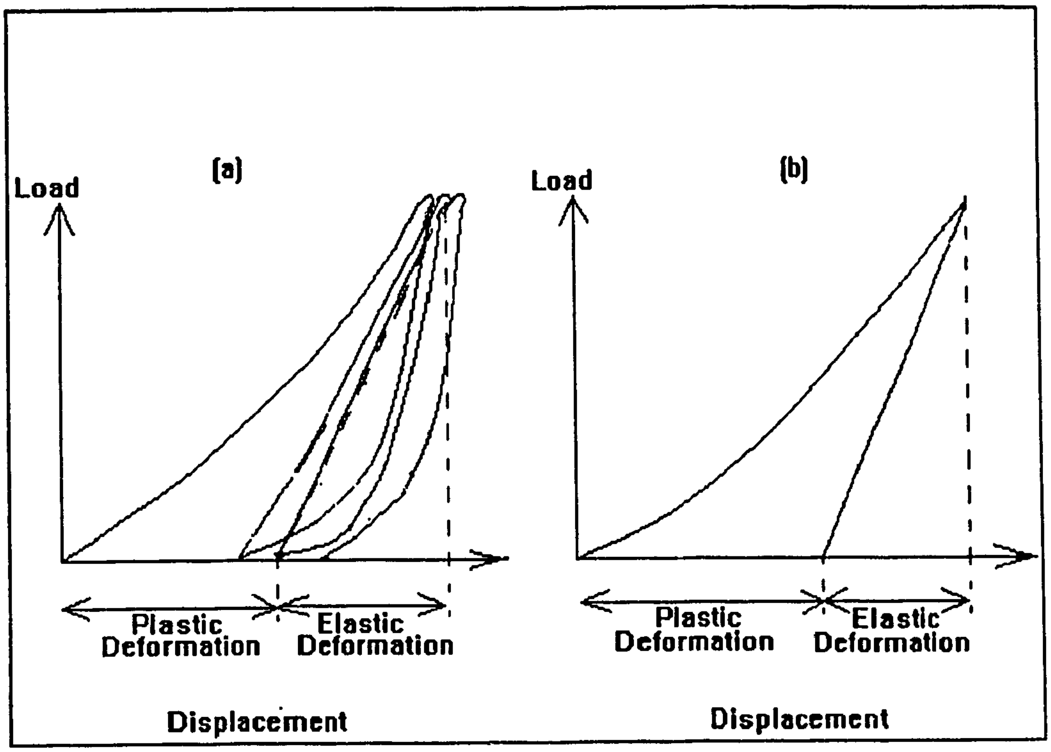


Figure 4.6: Load-displacement curves : (a) Actual, (b) Idealized from constrained modulus tests.

For a RTC:sand mixture of 70:30 respectively by weight (tested in a 12" mold) the value of M_c is found to be equal to $2.73*10^4$ psf (1.307 MPa) vide Table 4.4. Therefore, using equation 4.2 the modulus of elasticity can be obtained as:

$$E = [(1-2\mu)(1+\mu)*M_c]/(1-\mu)$$
$$= (1-2*0.2)(1+0.2)*(2.73*10^4)/(1-0.2)*144$$
$$= 170 \text{ psi. } (1172 \text{ KPa})$$

4.3.5 Poisson's ratio

For the structural analysis and design of flexible pavements as a multi-layer system, two primary mechanical parameters are essential: elastic modulus and Poisson's ratio. RTCs exhibit nonlinear elastic behaviour after the first cycle of load application which is accompanied by plastic (unrecoverable) strain. Therefore, the analysis of the flexible pavement (highway) systems using RTC-sand mixtures could be performed using elastic theory under traffic loads [5]. For such analysis, Poisson's ratio is essential in addition to the resilient modulus. To measure the Poisson's ratio directly in a uniaxial (unconfined) compression test, the RTCs were compacted in a 12-in. (0.305 m) mold to a height of 10-in. (0.254 m) and subjected to an axial pressure of 120 psf (5.74 KPa). At 120 psf (5.74 KPa), the mold was removed and four segments of a PVC membrane were placed on the sides of the standing specimen. These segments were attached together

Table 4.4: Subgrade Modulus Data ($\mu = 0.2$)

Mold size (in)	Sand Type	% of RTCs	% of Sand	Constrained Mod. M_c (psf)	Young Mod.E (psi)	Avg. E (psi)
6	out-wash	30	70	$3.52*10^5$	2200	1780
12	"	30	70	$2.17*10^5$	1356	
6	"	50	50	$9.01*10^4$	563	450
12	"	50	50	$5.56*10^4$	347	
6	"	70	30	$2.33*10^4$	145	160
12	"	70	30	$2.73*10^4$	170	
6	"	100	0	$2.06*10^4$	128	135
12	"	100	0	$2.24*10^4$	140	

(1-in. = 0.0254 m, 1 psf = 47.88 Pa, 1 psi = 6.9 KPa) using latex rubber as shown in figure 4.7 to allow lateral expansion with negligible lateral confinement. Then the axial pressure was increased in increments of about 65 psf (3.11 KPa) up to a peak pressure of 378 psf (18.09 KPa) while the lateral expansion of the specimen was measured at midheight by a tape and the vertical displacement was measured by a LVDT (Linear Variable Differential Transformer) [5]. Thus, the Poisson's ratio can be determined from the relation:

$$\mu = \text{lateral strain/longitudinal strain} \qquad (4.3)$$

4.3.6 Model Tests

Model embankments made up of RTCs-sand placed in layers simulating field test embankments were constructed in wooden boxes in Wisconsin Structure and Materials Laboratory. These model embankments were tested under repetitive loading and were analyzed for elastic deformation using finite element method (FEM) code known as ANSYS. Both in the model tests and the field, embankments constructed using RTCs initially underwent excessive plastic (unrecoverable) deformation followed by resilient behaviour to repetitive loading. "The boundary conditions of the model embankment are neither axisymmetric nor two dimensional, in fact it is basically three dimensional. However, the two dimensional analysis indicate that the difference between the three dimensional analysis and the two dimensional analysis is small relative to the variation of results due to the scatter in the material

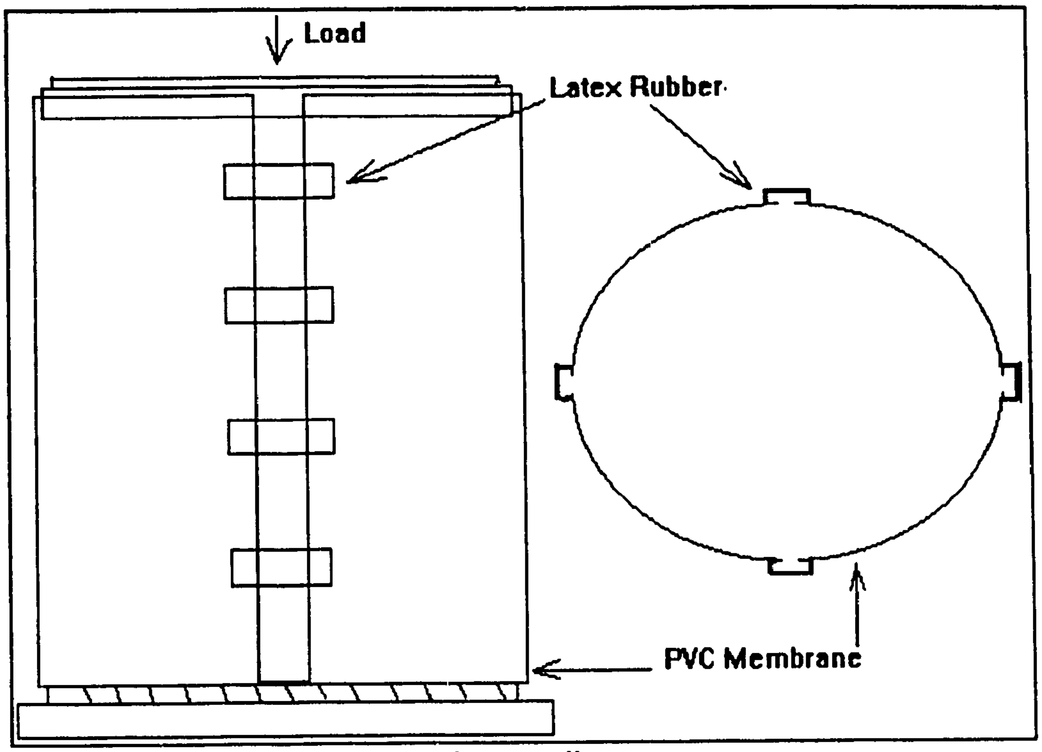


Figure 4.7: 12-inch Diameter membrane cell.

properties (approximately 15%). Hence the two dimensional analysis was used" [5].

A comparison between the measured (actual) and predicted (FEM) values indicate that an elastic finite element model provides a reasonably accurate response (surface deflections) of the material to loading [5]. But the same model assuming homogeneous halfspace and utilising Odemark's method of equivalent thickness with Boussinesq's equation give much higher surface deflections. This is because the materials in the wooden box has confinement along the sides and bottom. Besides, the material under the action of repetitive loading should experience higher modulus value from its original value which may be obtained by back calculation using Boussinesq's deflection equation. Thus, the model embankment consisting of 2 ft (0.61 m) sand and 3 ft (0.915 m) RTCs with initial elastic modulus of RTCs, E=257 psi (1.77 MPa) (37,000 psf) and Poisson's ratio $\mu=0.2$ as shown in figure 4.8 when subjected to repetitive loading of 8 kips (35.84 KN) and contact pressure of 58 psi (400 KPa) produces 0.38 inch (0.0096 m) surface deflection raising the modulus to 1934 psi (13.33 MPa) from its initial value of 257 psi (1.77 MPa) which can be seen from the following relationship:

Thus, using Boussinesq's deflection equation,

$$d_o = f*(1-\mu^2)*\sigma_o*a/E\ ;$$

$$\text{or} \quad E = 2*0.96*58*6.6/0.38$$

$$= 1934 \text{ psi } (13.33 \text{ MPa})$$

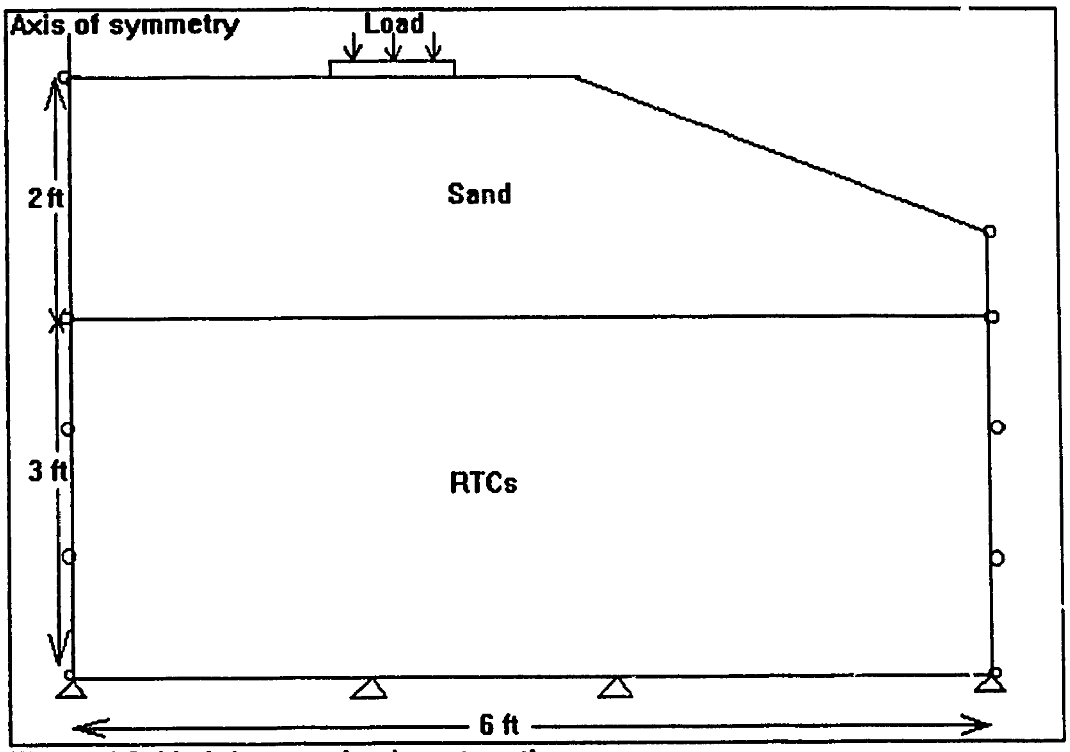


Figure 4.8: Model test embankment section.
[1 ft = 0.305 m]

where d_0 is the surface deflection, f is 2 for the uniformly distributed load, σ_o is the surface pressure and " a " is the radius of loaded area.

On the other hand, surface deflections of a typical box model as shown in appendix-A have been calculated by using Odemark-Boussinesq's equations considering the subgrade material as linear elastic. Surface deflections of the same model have also been determined by the iterative method of successive approximation as illustrated by Yang H. Huang [9] considering the subgrade material as nonlinear elastic. The results when compared show little difference. Odemark-Boussinesq method of linear elastic assumption gives surface deflection value of 2.86" (0.0726 m) while iterative method of approximation for nonlinear elastic assumption produces the surface deflection value of 2.14" (0.0543 m).

"Therefore, assumed moduli based on the tests on specimens (RTCs) can be used in the analysis of mass-behaviour of road sections built of RTCs" [5].

This means that the E-values obtained from the compaction and compressibility tests could be used for analysis of linear elastic half space by Odemark-Boussinesq method.

Chapter 5

Methodology

5.1 Introduction

As discussed in previous chapters the critical vertical compressive strain (ε_c) produced from the traffic loading and acting on the top of the subgrade and the critical horizontal tensile strain (ε_t) produced by the traffic and acting at the bottom of pavement layer are the two most important factors which govern the pavement analysis. Vertical compressive strain on top of subgrade layer and horizontal tensile strain at bottom of pavement layer could be obtained by Odemark's method of equivalent thickness and using Boussisesq's equations. For calculating vertical compressive strain (ε_c), the top layers consisting of different materials and having different moduli and Poisson's ratios over the subgrade are converted into one equivalent layer whose property (modulus and Poisson's ratio) will become same as that of the subgrade material. In other words, the entire pavement system will be transformed into one medium of subgrade material. The pavement model representing the equivalent thickness of the top layers over subgrade is shown in figure 5.1(a). The scenario thus formed maybe considered as a elastic half-space which has an infinite large area with a top plane over which superimposed loads are applied. Then Boussinesq's equations could be used to determine the vertical compressive strain on top of the subgrade. Likewise, for

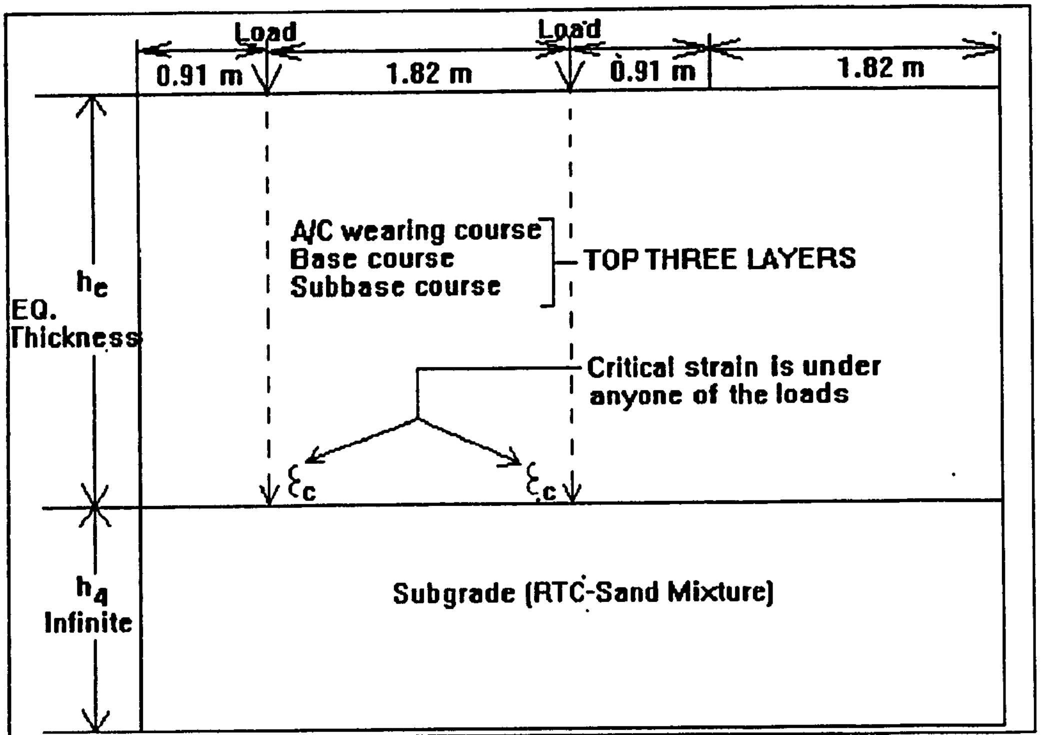


Figure 5.1(a): Pavement model showing the equivalent thickness of top layers over subgrade.

calculating the horizontal tensile strain (ε_t), the material of the pavement layer with modulus and Poisson's ratio is converted with respect to the material of base layer so that the pavement layer and base layer become one equivalent layer with modulus and Poisson's ratio of the material in base layer. Boussinesq's equations are then applied to determine the horizontal tensile strain at the bottom of pavement layer.

5.2 Pavement Model

Odemark-Boussinesq method requires an accurate model of the pavement structure and reasonable material parameters to predict the effects (pavement responses) of the loads on the materials.

Odemark-Boussinesq method used to analyze a typical four layer flexible pavement system consisting of an asphalt-concrete pavement layer, granular base layer, sandy subbase layer and RTC-sand mixture subgrade layer is shown in figure 5.1(b).

5.3 Strain contour (Load Vs. Equivalent thickness)

A strain contour may be defined as the points of the same strain value connected by a line. Thus, a strain contour line of magnitude of $150*10^{-6}$ is a line on which each and every point will represent a strain value of $150*10^{-6}$. A strain contour chart on the other hand, is a chart in which several strain contour lines representing different values of strains are drawn. Each strain contour line will represent a

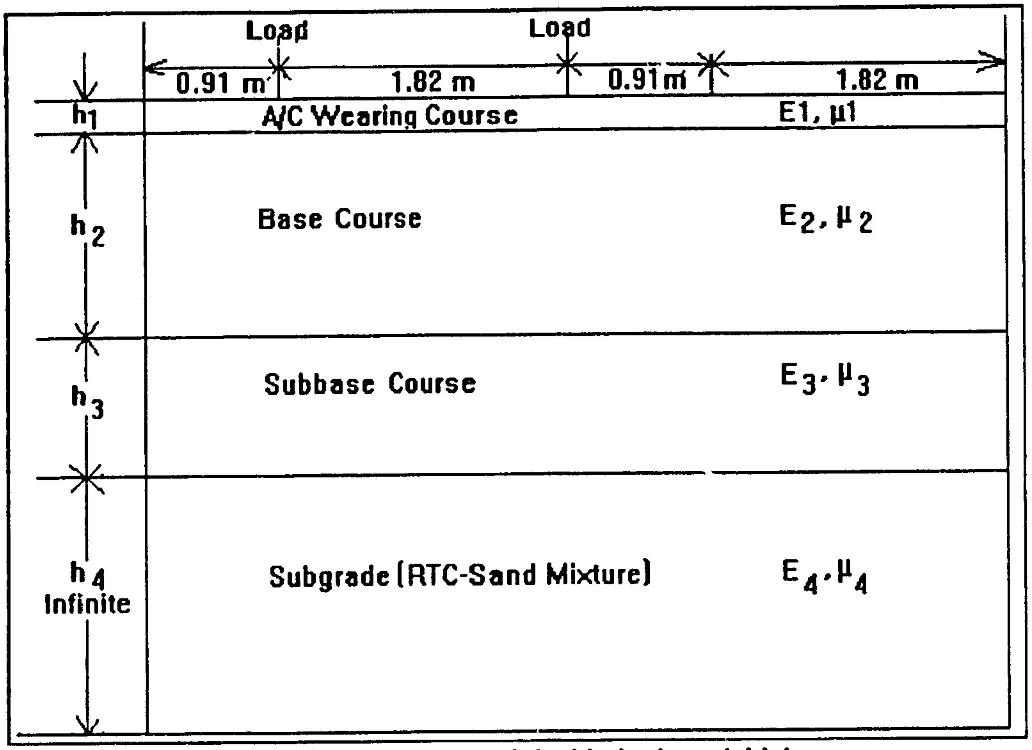


Figure 5.1(b): Pavement model with designed thickness.

particular value of strain and will never intersect with another strain contour line.

Vertical compressive strains are calculated using Odemark-Boussinesq method on the top of subgrade. An example hereunder explains how vertical compressive strains are obtained. Figure 5.2 shows a pavement model where a vertical load, P=9000 lbs. (40 KN) (standard wheel load) and the contact pressure due to wheel load on the pavement surface of 100 psi (690 KPa) are considered. The RTC-sand mixture (with a proportion of 50:50) in the subgrade layer has an elastic modulus of E=450 psi (3.10 MPa) and Poisson's ratio μ=0.2. This value of subgrade modulus, E is taken from the test results shown in Table 4.4 of chapter 4. An equivalent thickness of the top layers over subgrade has been taken as 120" (3.05 m). The reason for choosing the equivalent thickness of 120" (3.05 m) is because the subgrade modulus ranging from 125 psi (862 KPa) to 2250 psi (15.52 MPa) (for different mixtures of RTCs and sand as obtained from test results) and with reasonable parameters of top layers (actual layer thicknesses and moduli) above subgrade, the equivalent thicknesses approximately fall within the range from 96" (2.44 m) to 192" (4.88 m).

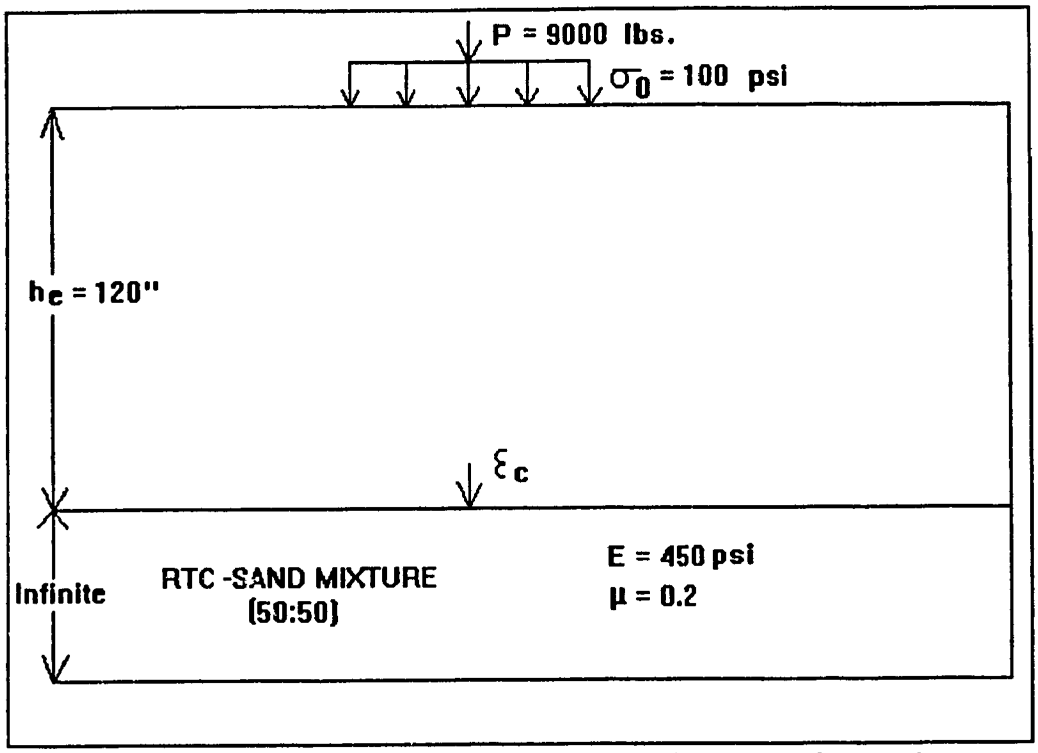


Figure 5.2: Pavement model for calculating vertical compressive strains. (Load Vs. Eq. thickness).

(1-in. = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Thus using Boussinesq's equation, the vertical compressive strain ε_c on top of subgrade can be determined by the following equation which is same as equation 3.3.

$$\varepsilon_c = \varepsilon_{120} = [(1+\mu)\sigma_o/E]*\{(z/a)/[1+(z/a)^2]^{1.5} - (1-2\mu)\{(z/a)/[1+(z/a)^2]^{0.5}-1\} \quad (5.1)$$

$$= [(1+0.2)100/450]*\{(120/5.35)/[1+(120/5.35)^2]^{1.5} - (1-2*0.2)\{(120/5.35)/[1+(120/5.35)^2]^{0.5}-1\}$$

$$= 687*10^{-6}$$

where a = radius of loaded area

$$= (P/\sigma_o *\pi)^{1/2}$$

$$= (9000/100*3.1416)^{1/2}$$

$$= 5.35" \ (0.1359 \text{ m})$$

Similarly, vertical compressive strains have been calculated for each wheel load of 8 kips, 10 kips and 12 kips (35.8, 44.8 and 53.7 KN) against equivalent thicknesses of 96", 120", 144", 168" and 192" (2.44, 3.05, 3.66, 4.27 and 4.88 m) with subgrade modulus value of E=135 psi, 160 psi and 1780 psi (0.93, 1.10 and 12.28 MPa). The E-values considered herein corresponds to a RTC:sand mixture of proportions of 100:0, 70:30 and 30:70 respectively and have been obtained from test results vide Table 4.4 of chapter 4. The values of vertical compressive strains thus obtained have been arranged in matrix form and shown in Table 5.1 and in Table B.1 to B.3 of Appendix B.

Table 5.1: Vertical comp. strains for E of subgrade=450 psi (μ=0.2) RTC:sand mix. of 50:50

Wheel load (lbs).	Eq. height (he) inch.	Ver. comp. strain (ε_c)....*10^{-6}
8000	96 120 144 168 192	954 611 425 312 239
9000	96 120 144 168 192	1073 687 478 351 269
10,000	96 120 144 168 192	1191 764 531 390 299
12,000	96 120 144 168 192	1429 916 637 468 358

(1-in. = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

A strain-contour chart has been plotted with wheel loads in the abscissa and equivalent thicknesses in the ordinate as shown in figure 5.3. Similar strain contour charts have also been prepared and shown in Figure B.1 to B.3 of Appendix B. These contours indicate the combined effects of wheel loads and equivalent thicknesses of the top layers over subgrade on the magnitude of the vertical compressive strains, ε_c.

It is observed from the figure of the strain contour charts that for a particular load the magnitude of ε_c decreases as the equivalent thickness increases and for a particular equivalent thickness, the magnitude of ε_c increases as the load increases.

Besides, the strain-contours represent a fundamental relationship between the applied load and equivalent thickness in producing the vertical compressive strains on the top of subgrade. For example, if a horizontal line is drawn in figure 5.3 corresponding to an equivalent thickness of 144-in. (3.66 m), then the vertical compressive strains for each load can be found.

On the other hand, if a vertical line is drawn corresponding to a load of 10-kips (44.8 KN) (wheel load), then the vertical compressive strains can be found for each equivalent thickness.

As such, the strain-contour charts can be used to determine the specific combination of equivalent thickness and

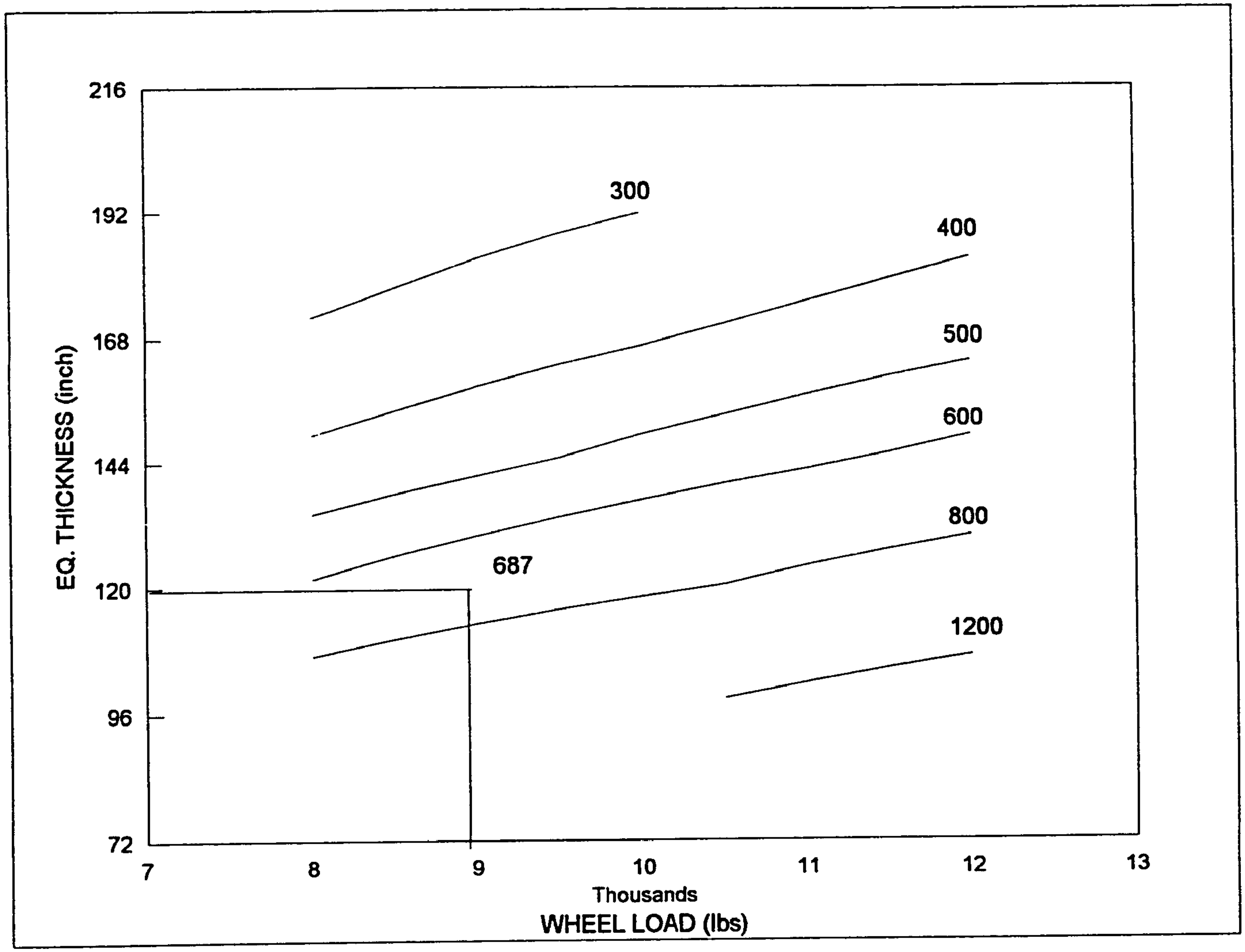


Figure 5.3 : Strain Contour Chart (E =450 psi) (u = 0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Wheel Load

wheel loads that can produce a given magnitude of the vertical compressive strain. In other words, by knowing the value of ε_c from the traffic load the equivalent thickness, h_e can be obtained for a particular subgrade material (with E and μ-value) from these-strain-contour charts. Therefore, these charts form the basis for the pavement design method developed in the next chapter.

5.4 Strain-contour (elastic modulus, E of subgrade Vs.Eq.thickness)

Strain contours as defined in section 5.3 are also drawn with different RTC-sand mixtures in a range of subgrade E-value from 125 psi (862 KPa) to 2250 psi (15.52 MPa) to cover the test results as shown in Table 4.4 and also for different μ-value ranging from 0.1 to 0.4. Equivalent thicknesses of top layers over subgrade have also been varied in the range from 96" (2.44 m) to 192" (4.88 m) for the reasons already described in section 5.3. The purpose for doing this is to use any RTC-sand mixture with any E and μ value within the range mentioned above and to obtain the corresponding strain value.

A pavement model for calculating vertical compressive strain is shown in figure 5.4 where the vertical load P is kept constant at the standard wheel load of 9000 lbs (40 KN). Contact pressure, σ_0 is considered to be 100 psi (690 KPa) and radius of loaded area, a=5.35" (0.1359 m) [$a=(P/\sigma_0*\pi)^{1/2}$] is obtained. Poisson's ratio of μ=0.2 and

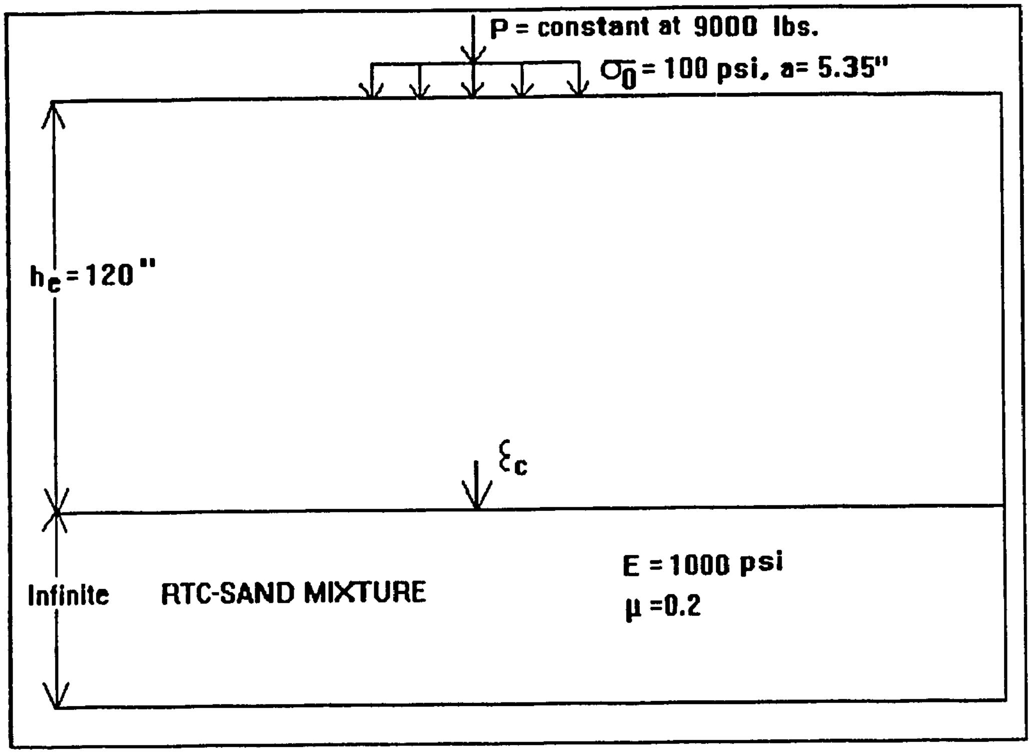


Figure 5.4: Pavement model for calculating vertical compressive strains . (Subgrade Modulus Vs.Eq. thickness).

(1-in. = 0.0254 m, 1 psi = 6.9 KPa, 1 lb. = 4.48 N)

elastic modulus, E=1000 psi (6.9 MPa) of subgrade material have been considered. This E value of 1000 psi (6.9 MPa) corresponds to a RTC:sand mixture of about 40:60 by weight. Besides, an equivalent thickness of top layers over subgrade has been chosen to be 120" (3.05 m).

Thus vertical compressive strain on top of subgrade is calculated by using Boussinesq's equation no 3.3 which is given by:

$$\varepsilon_c=\varepsilon_{120}=[(1+\mu)\sigma_o/E]*\{(z/a)/[1+(z/a)^2]^{1.5}-(1-2\mu) *\{(z/a)/[1+(z/a)^2]^{0.5}-1\} \quad (5.2)$$

$$= [(1+0.2)100/1000]*\{(120/5.35)/[1+(120/5.35)^2]^{1.5} -(1-2*0.2)\{(120/5.35)/[1+(120/5.35)^2]^{0.5}-1\}$$

$$= 309*10^{-6}$$

Similarly, vertical compressive strains have been calculated for each value of subgrade modulus E of 125 psi, 250 psi, 500 psi, 750 psi, 1000 psi, 1250 psi, 1500 psi, 1750 psi, 2000 psi and 2250 psi (862, 1724, 3448, 5172, 6896, 8620, 10344, 12068, 13792 and 15516 KPa) against equivalent thicknesses of 96", 120", 144", 168" and 192" (2.44, 3.05, 3.66, 4.27 and 4.88 m). Poisson's ratios of μ=0.1, 0.3 and 0.4 have been considered for each set of computations. The standard wheel load P=9000 lbs. (40 KN) has been kept constant.

The value of vertical compressive strains thus obtained have been arranged in the form of a matrix as shown in Table 5.2 (a) & (b) for μ=0.2. Similarly values of vertical compressive strains for μ=0.1, 0.3 and 0.4 have been arranged in the form of matrix as shown in Table B.4 to B.9 of Appendix B.

Two strain-contour charts have been plotted for a value of subgrade Poisson's ratios of μ=0.2 as shown in figure 5.5 and 5.6. The horizontal axis represents the value of elastic modulus E of subgrade material (E=125 psi to 1250 psi (862 to 8620 KPa) in figure 5.5 and 1250 psi to 2250 psi (8620 to 15516 KPa) in figure 5.6) to cover the range of moduli for different mixture of R.T.C-sand in the subgrade and the vertical axis represents the equivalent thicknesses of the top layers over subgrade, h_e of 96", 120", 144", 168" and 192" (2.44, 3.05, 3.66, 4.27 and 4.88 m). Similarly contour charts for subgrade μ-value of 0.1, 0.3 and 0.4 have been drawn and shown in Figure B.4 to B.9 of Appendix B.

The value of vertical compressive strain has a combined effect of both the subgrade modulus and equivalent thickness. It can be observed from Table 5.2 (a) & (b) that for a particular elastic modulus of subgrade the value of the vertical compressive strain decreases as the equivalent height increases. Again, for a particular equivalent thickness the value of vertical compressive strain decreases as the elastic modulus of the subgrade increases. Further, it is also

Table 5.2 (a): Vertical compressive strains for μ of 0.2

Elastic modl. of subgrade, E (psi)	Equivalent thickness he (inch)	Vertical compressive strain, ε_c.... ($*10^{-6}$)
125	96 120 144 168 192	3863 2476 1721 1265 968
250	96 120 144 168 192	1931 1238 860 632 484
500	96 120 144 168 192	965 619 430 316 242
750	96 120 144 168 192	643 412 286 210 161
1000	96 120 144 168 192	482 309 215 158 121

(1-in. = 0.0254 m, 1 psi = 6.9 KPa)

Table 5.2 (b): Vertical compressive strains for μ of 0.2

Elastic modl. of subgrade, E (psi)	Equivalent thickness he (inch)	Vertical compressive strain, ε_c.... (*10^{-6})
1250	96 120 144 168 192	386 247 172 126 96
1500	96 120 144 168 192	321 206 143 105 80
1750	96 120 144 168 192	275 176 122 90 69
2000	96 120 144 168 192	241 154 107 79 60
2250	96 120 144 168 192	214 137 95 70 53

(1-in. = 0.0254 m, 1 psi = 6.9 KPa)

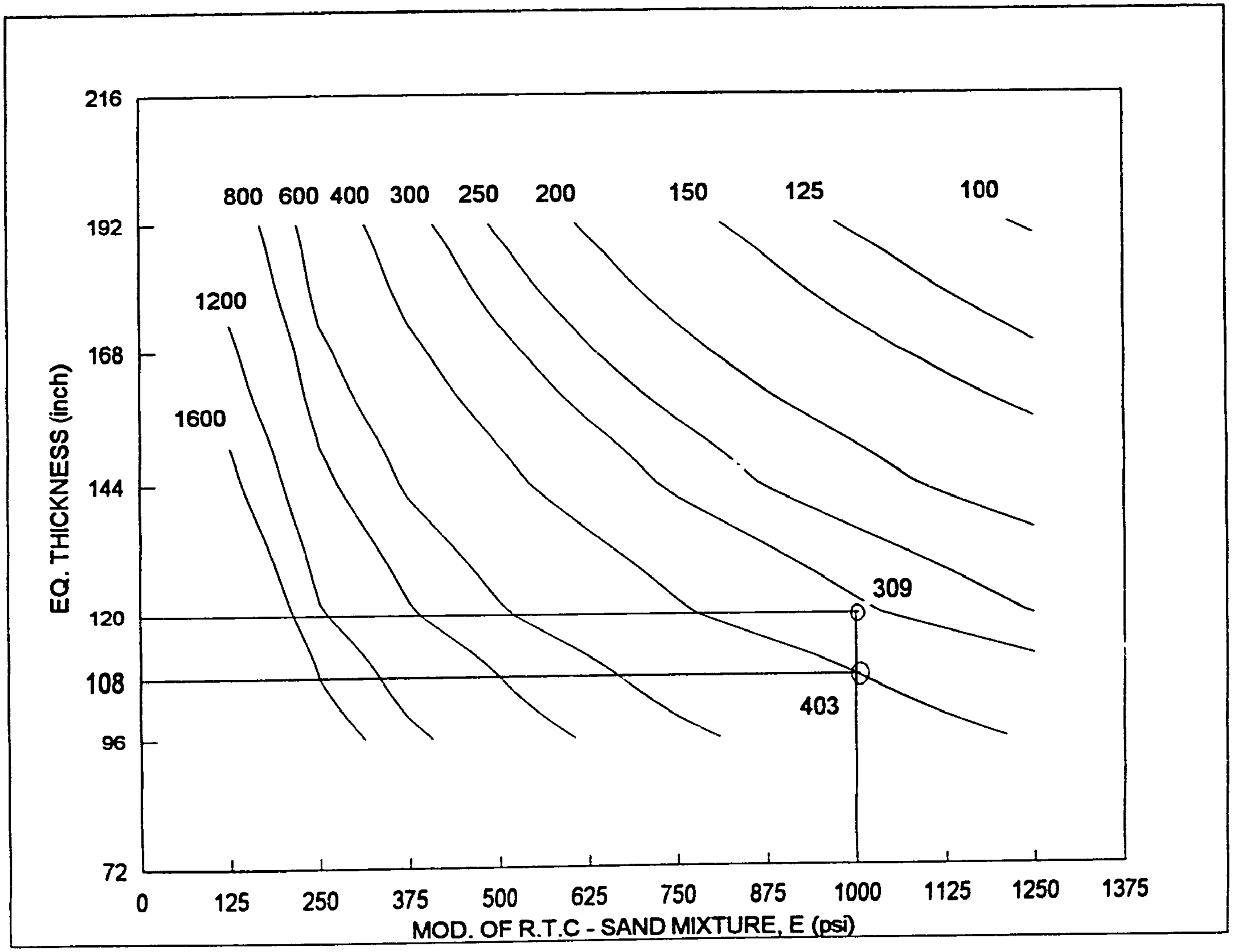


Figure 5.5 : Strain Contour Chart (u =0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

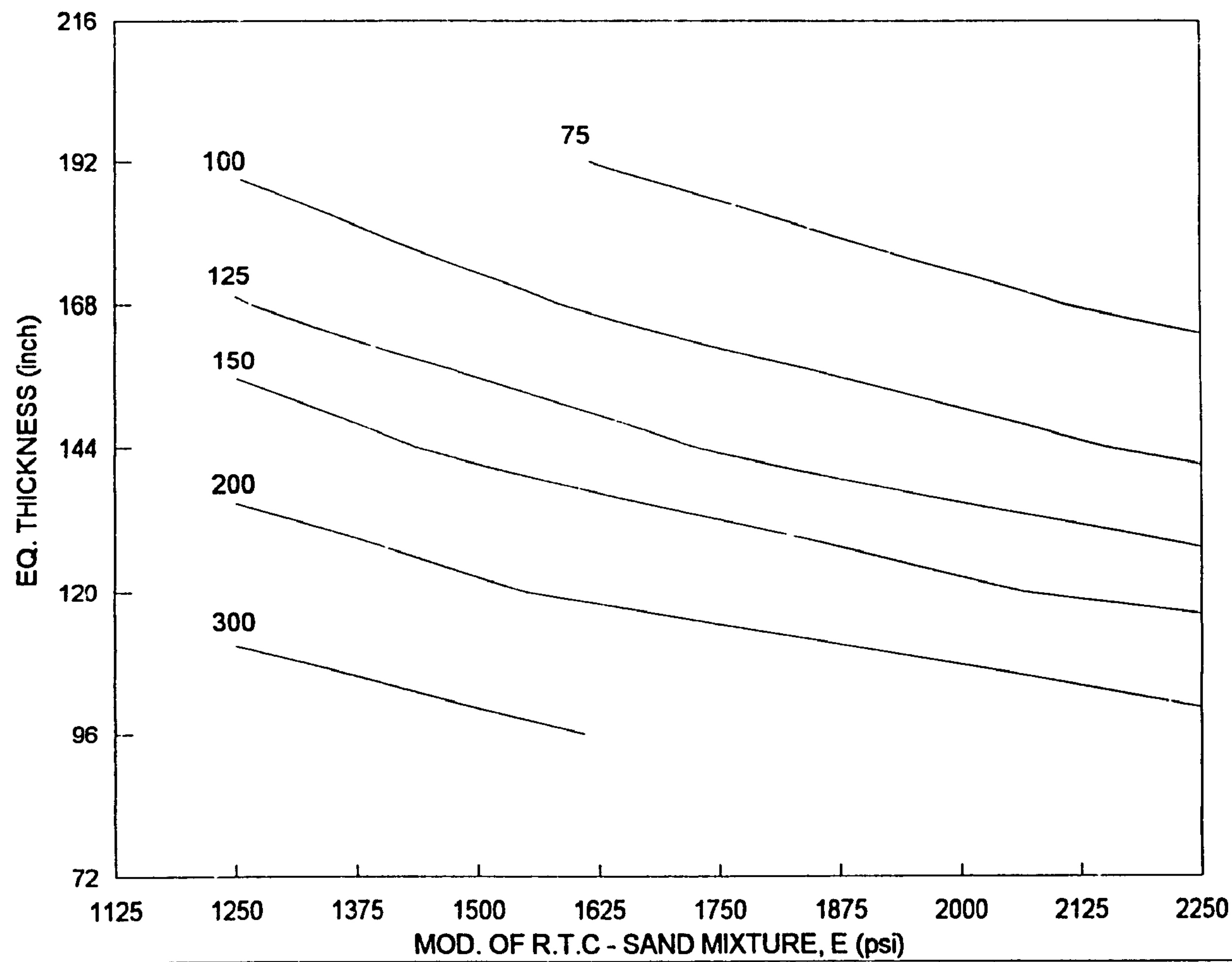


Figure 5.6 : Strain Contour Chart (u =0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

observed from Table 5.2 (a) that the value of vertical compressive strain for an elastic modulus E of 125 psi (862 KPa) and an equivalent thickness, h_e of 96" (2.44 m) is 3863 whereas that for E=1250 psi (8620 KPa) and h_e=96" (2.44 m) is 386 from table 5.2 (b). This shows that as E increased 10 times the value of ε_c decreased 10 times for a constant equivalent thickness, h_e of 96" (2.44 m). This observation leads to the conclusion that the vertical compressive strains on top of subgrade caused by standard wheel load of 9-kips (40 KN) is inversely proportional to the value of elastic modulus of subgrade material.

As such the strain-contour charts can be used to determine the specific combination of equivalent thickness and elastic modulus of subgrade for a particular subgrade Poisson's ratio that produce a given magnitude of the vertical compressive strain. In other words, by knowing the value of ε_c from traffic load, the equivalent thickness could be found for a particular E and μ-value of the subgrade material. These strain-charts form the basis for the pavement design method described in the next chapter.

5.5 Plotting of curves (horizontal tensile strain Vs. actual pavement thickness)

Horizontal tensile strain, (ε_t) generated by the wheel load at the bottom of the pavement layer is considered as the critical strain. This is the basis for the design of the thickness of pavement layer. Horizontal tensile strain at the bottom of pavement layer could be obtained by using Odemark-Boussinesq method and different charts are developed against horizontal tensile strains and pavement thicknesses which would later be used for finding the design thickness of pavement layer.

Thus horizontal tensile strains at the bottom of pavement layer have been calculated using Odemark's method of equivalent thickness with respect to base layer and then using Boussinesq's equations for different moduli of pavement and base layer. Standard wheel load of 9000 lbs (40 KN), contact pressure of 100 psi (690 KPa), Poisson's ratio of 0.2 for both the pavement and base layer, and moduli of pavement and base of 290,000 psi (2000 MPa) and 43,500 psi (300 MPa) respectively, have been considered. Figure 5.7 shows the pavement model for calculating horizontal tensile strain at the bottom of pavement layer. A pavement thickness of 3" (0.0762 m) has been considered for calculating the horizontal tensile strain.

From Odemark's method the equivalent thickness of pavement layer with respect to base

$$h_{e1} = c_f * h_1 * (E_1/E_2)^{1/3} \qquad (5.3)$$

$$= 1.182*3*(290{,}000/43{,}500)^{1/3}$$

$$= 6.67\text{"} \ (0.1694 \text{ m}).$$

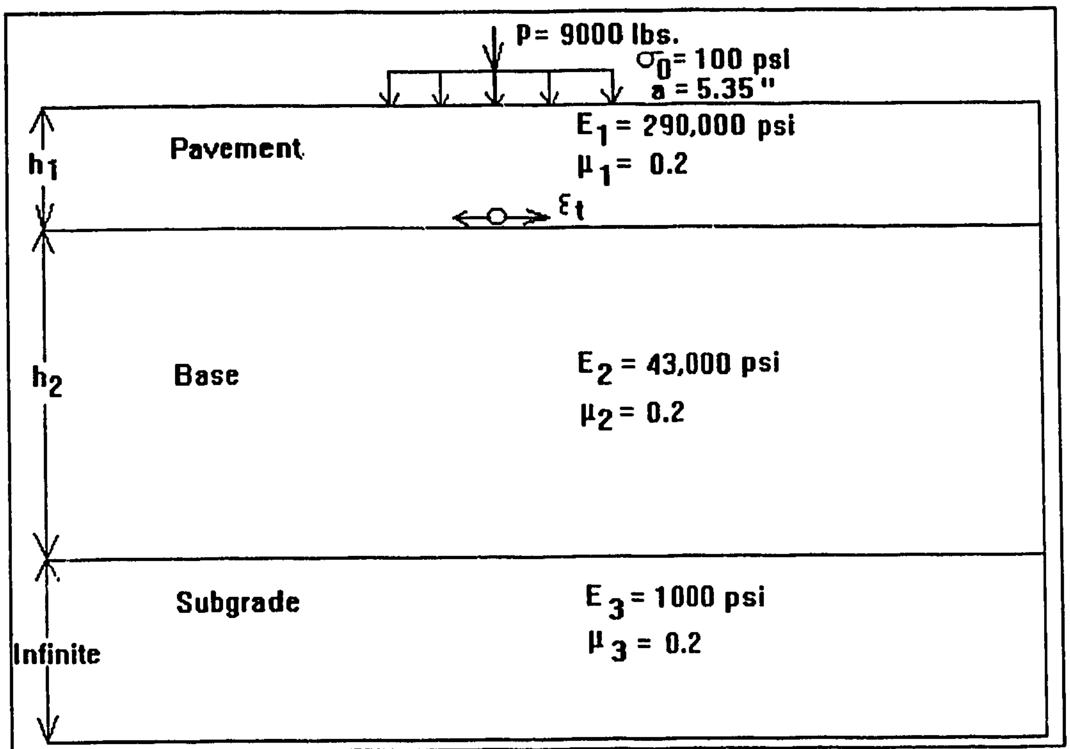


Figure 5.7: Pavement model for calculating horizontal tensile strain.

(1-in. = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

where,

$$c_f = 0.96+0.83*a/h_1*(E_2/E_1) \quad (5.4)$$

$$= 0.96+0.83*5.35/3*43500/290000$$

$$= 1.182.$$

and $$a= (9000/100*\pi)^{1/2}$$

$$= 5.35" \ (0.1359 \text{ m}).$$

From Boussinesq's equation no. 3.6, horizontal tensile strain,

$$\varepsilon_t=h_1/2*R_c \quad (5.5)$$

where R_c=Radius of curvature which can be obtained by equation no.3.7:

$$R_c=E_2*a/[(1-\mu^2)*\sigma_o]/\{1+[1+1.5/(1-\mu)]*(z/a)^2\}*[1+(z/a)^2]^{2.5}$$

$$= [43.5*5.35/(1-0.2^2)*0.100]/\{1+[1+1.5/(10.2)] \quad (5.6)$$

$$*(6.67/5.35)^2\}*[1+(6.67/5.35)^2]^{2.5}$$

$$= 4623.33" \ (117.43 \text{ m})$$

Thus, horizontal tensile strain,

$$\varepsilon_t=h_1/2R_c =3/2*4623.33 = 324*10^{-6}$$

Similarly horizontal tensile strains for different thicknesses of pavement layer of 6", 9", 12" (0.1524, 0.2286, 0.3048 m) and for combination of pavement and base moduli of 435,000 psi (3000 MPa) and 58,000 psi (400 MPa); and 580,000 psi (4000 MPa) and 72,500 psi (500 MPa) respectively have been calculated as shown in Table 5.3 (b) & (c). Three curves have been plotted representing the above combination of moduli with horizontal tensile strains in the ordinate and actual pavement thickness in the abscissa as shown in figure 5.8.

Table 5.3(a): Horizontal tensile strain at the bottom of pavement layer.
[For E_1=290,000 psi (2000 Mpa) and E_2=43,500 psi (300 Mpa)]

Actual pavement thickness (inch)	Equivalent thickness of pavement with respect to base (inch)	Horizontal tensile strain...*10^{-6} (psi)
3	5.65	324
6	11.30	210
9	16.95	150
12	22.60	102

Table 5.3(b):
[For E_1=435,000 psi (3000 Mpa) and E_2=58,000 psi (400 Mpa)]

Actual pavement thickness (inch)	Equivalent thickness of pavement with respect to base (inch)	Horizontal tensile strain...*10^{-6} (psi)
3	5.87	236
6	11.74	148
9	17.61	104
12	23.48	70

Table 5.3(c):
[For E_1=580,000 psi (4000 Mpa) and E_2=72,500 psi (500 Mpa)]

Actual pavement thickness (inch)	Equivalent thickness of pavement with respect to base (inch)	Horizontal tensile strain...*10^{-6} (psi)
3	6.00	186
6	12.00	114
9	18.00	79
12	24.00	53

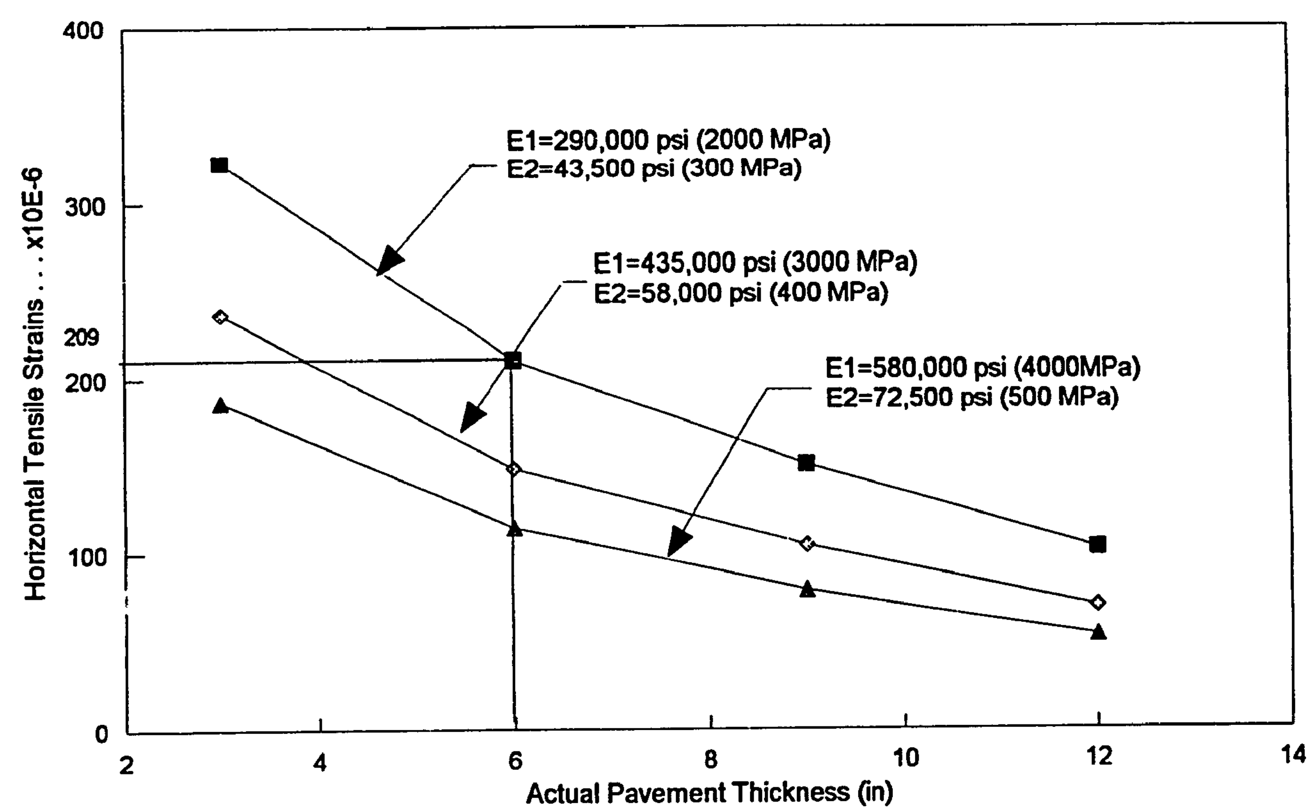


Figure 5.8: Horizontal Tensile Strain vs Actual Thickness of A/C layer (Pavement)

From these curves, knowing the value of horizontal tensile strain (ε_t) produced by the traffic loading and the moduli of pavement and base layer, the actual thickness of pavement could be determined.

Chapter 6

Pavement design method

6.1 Introduction

The design method requires that all traffic loads be factored to an equivalent 18000 lbs. (80 KN) standard axle load i.e, 9000 lbs. (40 KN) wheel load.

The design criteria is based on the principle that due to the traffic load on pavement structure, (a) vertical compressive strains will be developed on the top of subgrade which is the critical value (ε_c) causing permanent deformation on the pavement and (b) horizontal tensile strains will be produced at the bottom of A/C layer (pavement) which is the critical value (ε_t) causing surface cracking. The material parameters for each layer have been determined from laboratory tests as discussed earlier in chapter 4. These values are then incorporated in the strain-contour charts to obtain the equivalent thickness (h_e) of the top layers above the subgrade and the actual thickness of A/C layer (pavement).

6.2 Pavement design method

The objective of the pavement design method is to determine the thicknesses of pavement, base and subbase layers above the subgrade which consists of RTC-sand mixture. The parameters (E and μ) for different layers including the RTC-sand mixture and axle loads due to the traffic volume are provided. The design method follows through several steps which are interconnected. For this purpose a flow diagram is developed as shown in figure 6.1. The steps shown in the flow diagram are described in separate sections below.

The vertical compressive strains, ε_c on top of subgrade is obtained by using Odemark-Boussinesq method which assumes the materials under the action of load to be semi infinite mass (half space). Strain contour charts are then developed using material parameters (E and μ-values) against equivalent thicknesses which has already been described in chapter 5.

6.3 Traffic load repetition

The design method initially requires that the daily volume of traffic on the pavement be converted into the number of 18,000 lbs. (80 KN) load repetitions per year. This conversion to equivalent 18,000 lbs. (80 KN) single axle load applications (EAL) is done by multiplying the number of vehicles in each weight class (N_v) by the load equivalency factor (f_L). Thus, the traffic load per year can be obtained from the following equation:

$$N_Y = (365 \text{ days/year}) * (N_v * f_L) \tag{6.1}$$

The load equivalency factor (f_L) is shown in Table 6.1. The values shown in the table are for a present serviceability index, P of 2.5. This index represents a rating given to road based on high speed tests as well as on

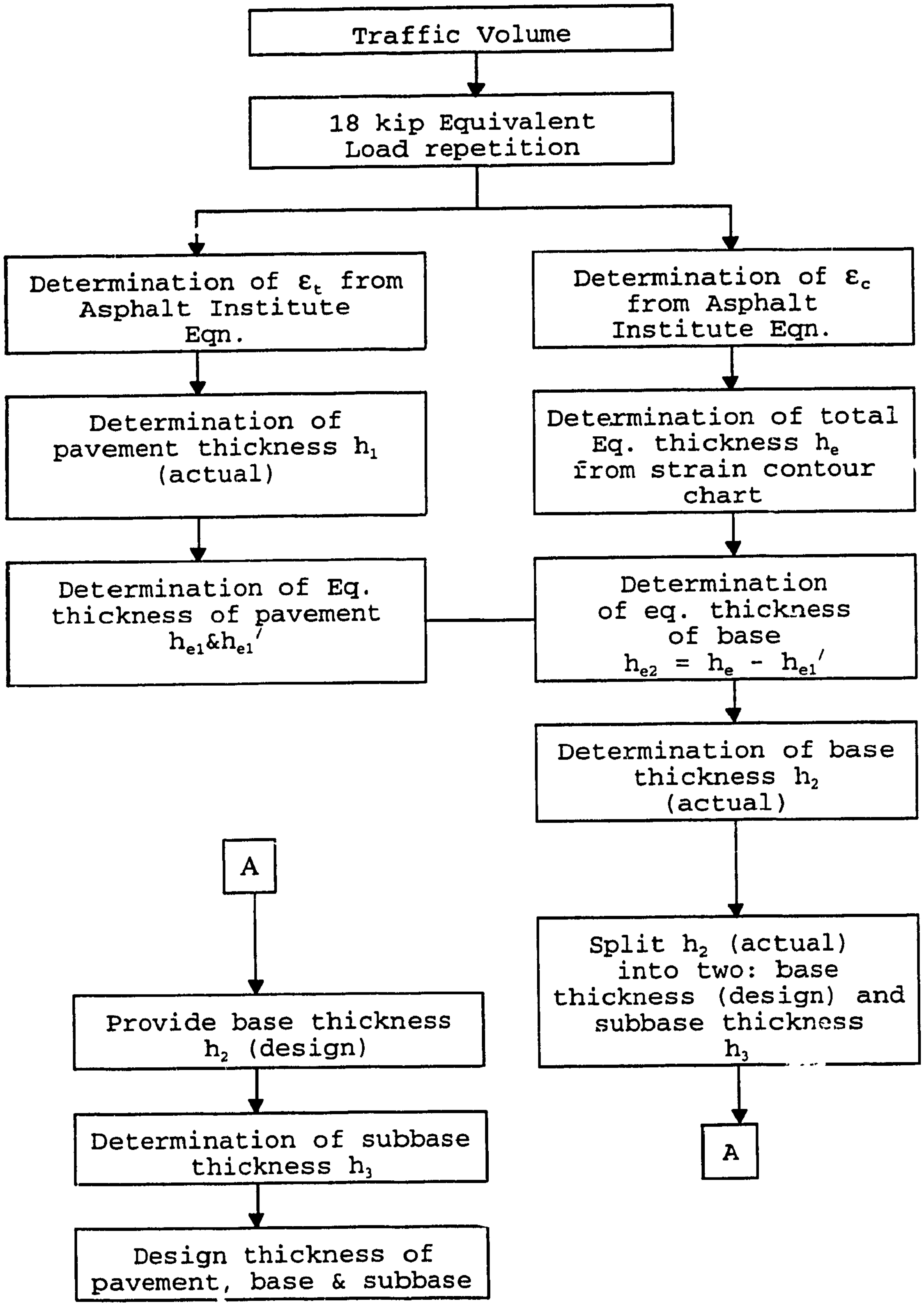


Figure 6.1: Flow diagram for design method

Table 6.1: Load Equivalence Factors (p= 2.5)

Loads (kN)	Single Axles Structural Number SN			Tandam Axle Sets Structural Number SN		
	1	4	6	1	4	6
9	0.0004	0.0002	0.000			
26	0.01	0.01	2			
44	0.08	0.10	0.01	0.01	0.01	0.01
62	0.33	0.39	0.08	0.03	0.03	0.02
80	1.00	1.00	0.34	0.07	0.09	0.07
98	2.48	2.09	1.00	0.16	0.21	0.17
115	5.33	3.91	2.30	0.33	0.40	0.34
133	10.31	6.83	4.48	0.61	0.70	0.63
151	81.41	11.34	7.79	1.06	1.11	1.08
169	30.90	18.06	12.51	1.75	1.68	1.73
178	39.26	22.40	18.98	2.21	2.03	2.14
195			23.04	3.41	2.88	3.16
213				5.08	3.98	4.49

Table 6.2: Growth Factors

Design Period (yr)	Annual Growth Rate (%)					
	0	2	4	6	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0
5	5.0	5.20	5.42	5.64	5.87	6.11
10	10.0	10.95	12.01	13.18	14.49	15.94
15	15.0	17.29	20.02	23.28	27.15	31.77
20	20.0	24.20	29.78	36.79	45.76	52.28

Source: Oglesby H. Clarkson and Hicks R. Gary [13].

deformations and deteriorations of the pavement. Oglesby and Hicks [13] have given a detailed explanation on serviceability index and its derivation.

Growth factors as shown in Table 6.2 may also be used, if required. These factors allow the calculations to take into account the annual increase in traffic over the design period.

Hence the total number of EAL in the design life of the pavement (N) is obtained by:

$$N=S*N_Y \quad (6.2)$$

where, S = the design life of pavement in years and

N_Y = the load repetitions per year.

6.4 Determination of pavement thickness (h_1)

Asphalt Institute method determines the critical horizontal tensile strain at the bottom of pavement layer. This limiting strain value corresponding to traffic axle load must not be exceeded and is the basis for finding the pavement thickness (actual) from the appropriate curve. For this purpose, material properties (E and μ-values) of pavement and base layer are required.

From the Asphalt Institute Equation no. 3.12

$$\varepsilon_t=[N/18.4*c*4.32*10^{-3}*E^{-0.854}]^{-1/3.29}$$

the critical horizontal tensile strain, ε_t due to traffic and corresponding total load repetitions (N) can be obtained.

The value of ε_t thus obtained could be inserted into the appropriate curve (figure 5.8) for the specific moduli of pavement and base course material to obtain the actual thickness of pavement, h_1.

The actual thickness of pavement h_1 could then be converted into the equivalent thickness of pavement h_{e1} with respect to base layer by Odemark's method of equivalent thickness by equation no. 3.9

$$he_1=C_f*h_1*(E_1/E_2)^{1/3}$$

This equivalent thickness h_{e1}, is again converted into h_{e1}' with respect to subgrade layer by the same procedure ie.

$$h_{e1}'=C_f*h_{e1}*(E_2/E_4)^{1/3}$$

where C_f=1.00 for the first interface and E_1, E_2 and E_4 are moduli of pavement, base and subgrade respectively.

6.5 Determination of base thickness (h_2)

Asphalt Institute method also determines the critical vertical compressive strain on top of subgrade layer. This strain value corresponding to the traffic axle load must not be exceeded and is the basis for finding the equivalent thickness of the top layers over subgrade using strain-contour charts. For this the subgrade material properties (E and μ-values) are also needed.

From the Asphalt Institute Equation no. 3.13

$$\varepsilon_c=(N/1.36*10^{-9})^{-1/4.48}$$

the critical vertical compressive strain, ε_c at the top of subgrade due to traffic and corresponding total load repetitions (N) can be determined. This value of ε_c is inserted into the appropriate strain-contour chart of modulus of RTC-sand mixture Vs. equivalent thickness in figure 5.5 to obtain the total equivalent thickness, h_e of the top layers over subgrade with respect to the subgrade modulus. The elastic modulus of subgrade E_4 and Poisson's ratio μ_4 are used to determined h_e from the strain-contour charts.

Now as the total equivalent thickness, h_e of top layers with respect to subgrade modulus is known, and the equivalent thickness of pavement layer with respect to subgrade h_{e1}' is also known as described in section 6.4, the equivalent thickness of base with respect to modulus of subgrade h_{e2} could be determined from the following relationship;

$$h_{e2}=h_e-h_{e1}'$$

The equivalent thickness of base h_{e2} thus obtained could once again be converted into actual thickness of base h_2(actual) from Odemark's equation no. 3.9

$$h_{e2}=C_f*h_2(\text{actual})*(E_2/E_4)^{1/3}$$

or, $$h_2(\text{actual})=h_{e2}/C_f*(E_2/E_4)^{1/3}$$

where C_f=0.8 for the multilayer system and E_2 and E_4 are moduli of base and subgrade respectively.

6.6 Determination of subbase thickness (h_3)

If the thickness of base course, h_2(actual) is large then it can be split into base thickness of h_2(design) and subbase thickness of h_3. The thickness of subbase can be obtained as follows:

Let, $h_2(\text{actual})=h_2(\text{design})+h_3$

or, $h_3=h_2(\text{actual})-h_2(\text{design})$

Now using Odemark's method h_3 can be obtained as:

$$h_3=C_f[h_2(\text{actual})-h_2(\text{design})]*[E_3/E_4]^{1/3}$$

where, C_f=0.8 for multilayer system and E_3 and E_4 are moduli of subbase and subgrade layers respectively.

6.7 Design example

The axle load due to traffic on the pavement is equivalent to 400 standard 18,000 lbs. (80 KN) load applications/day for a service life of 15 years. The subgrade material is assumed to be linear elastic with a modulus of elasticity, E of 1,000 psi (6.9 MPa) (corresponding to RTC:sand mixture of about 40:60 by weight) and a Poisson's ratio, μ of 0.2. The base and pavement layer materials have E-values of 43,500 psi (300 Mpa) and 290,000 psi (2,000 Mpa) with μ-values of 0.2 each respectively.

Solution

(Step 1) Axle load due to traffic on the pavement is given which is equal to 400 standard 18,000 lbs. (80 KN) load applications/day.

(Step 2) Determination of total number of load repetitions, N:

The number of load repetitions to failure,

$$N = (400 \text{ loads/day})*(365 \text{ days/year})*(15 \text{ years})$$
$$= 2{,}190{,}000.$$

(Step 3) Determination of ε_t from Asphalt Institute equation:

Using Asphalt Institute equation no. 3.12,

Horizontal tensile strain,

$$\varepsilon_t = [N/18.4*(c)*4.32*10^{-3}*E^{-0.854}]^{-1/3.29}$$
$$= [2{,}190{,}000/1.00*18.4*4.32*10^{-3}*(290{,}000)^{-0.854}]^{-1/3.29}$$
$$= 209*10^{-6}.$$

(Step 4) Determination of pavement thickness h_1(actual) from appropriate curve:

Using the value of ε_t=209*10^{-6} in fig 5.8 the actual pavement thickness, h_1=6" (0.1524 m) is obtained.

(Step 5) Determination of equivalent thickness of pavement with respect to base h_{e1} and subgrade h_{e1}':

The actual pavement thickness, h_1 can be converted into equivalent thickness of pavement, h_{e1} with respect to base by Odemark's method of equivalent thickness in the following way:

$$h_{e1} = c_f*h_1*(E_1/E_2)^{1/3}$$
$$= 1.00*6*(290{,}000/43{,}500)^{1/3}$$
$$= 11.3\text{" } (0.287 \text{ m}).$$

where c_f = 1.00 for the first interface,

E_1 = modulus of pavement and

E_2 = modulus of base.

This equivalent thickness of pavement, h_{e1} is again converted into h_{e1}' with respect to subgrade i.e,

$$h_{e1}' = c_f * h_{e1} * (E_2/E_4)^{1/3}$$
$$= 1.00*11.3*(43,500/1,000)^{1/3}$$
$$= 39.75" \ (1.009 \text{ m}).$$

where, c_f = 1.0

and E_4 = subgrade modulus.

(Step 6) Determination of (ε_c) from Asphalt Institute equation:

From Asphalt equation no. 3.13, the vertical compressive strain,

$$\varepsilon_c = (N/1.36*10^{-9})^{-1/4.48}$$
$$= (2,190,000/1.36*10^{-9})^{-1/4.48}$$
$$\approx 403*10^{-6}.$$

(Step 7) Determination of total equivalent thickness h_e with respect to subgrade from appropriate strain contour chart: Using the value of ε_c =403*10^{-6} in fig. 5.5, for a subgrade modulus, E=1000 psi (6.9 MPa), μ=0.2, the total equivalent thickness, h_e of the top layers above subgrade is obtained which is equal to 108" (2.743 m).

(Step 8) Determination of equivalent thickness of base h_{e2} with respect to subgrade:

The equivalent thickness of base h_{e2} with respect to subgrade can be calculated from the following relationship:

$$h_{e2} = h_e - h_{e1}'$$
$$= 108-39.75$$
$$= 68.25" \ (1.733 \text{ m}).$$

(Step 9) Determination of base thickness h_2(actual):

The equivalent thickness of base could be converted into base thickness, h_2(actual) from Odemark's equation in the following way:

$$h_{e2} = c_f * h_2(\text{actual}) * (E_2/E_4)^{1/3}$$

or, $$h_2(\text{actual}) = \{h_{e2}/c_f * (E_2/E_4)^{1/3}\}$$
$$= 68.25/0.8*(43{,}500/1{,}000)^{1/3}$$
$$= 24.25" \ (0.6159 \text{ m}).$$

where, c_f = 0.8 for the multilayer structure.

(Step 10) Splitting of base thickness h_2(actual) into base thickness h_2(design) and subbase thickness h_3:

As the base thickness h_2(actual) is large, it is spilt into base thickness h_2(design) and a subbase thickness h_3.

(Step 11) Determination of base thickness h_2(design):

Let base thickness h_2(design) be 12" (0.3048 m).

(Step 12) Determination of subbase thickness h_3:

The subbase thickness, h_3 can be obtained from the following relationship:

$$h_3 = c_f * [h_2(\text{actual}) - h_2(\text{design})] * [E_3/E_4]^{1/3}$$
$$= 0.8 * (24.25 - 12) * (8333/1000)^{1/3}$$
$$= 19.86$$
$$\approx 20" \; (0.508 \text{ m}).$$

where c_f = 0.8 for the multilayer structure and E_3=modulus of subbase layer which has been considered to be 8333 psi (57.43 MPa). Therefore, using Asphalt Institute Equations, utilising Odemark-Boussisesq method and appropriate strain-contour charts the actual thicknesses of different layers of the pavement structure have been obtained which is shown in fig. 6.2.

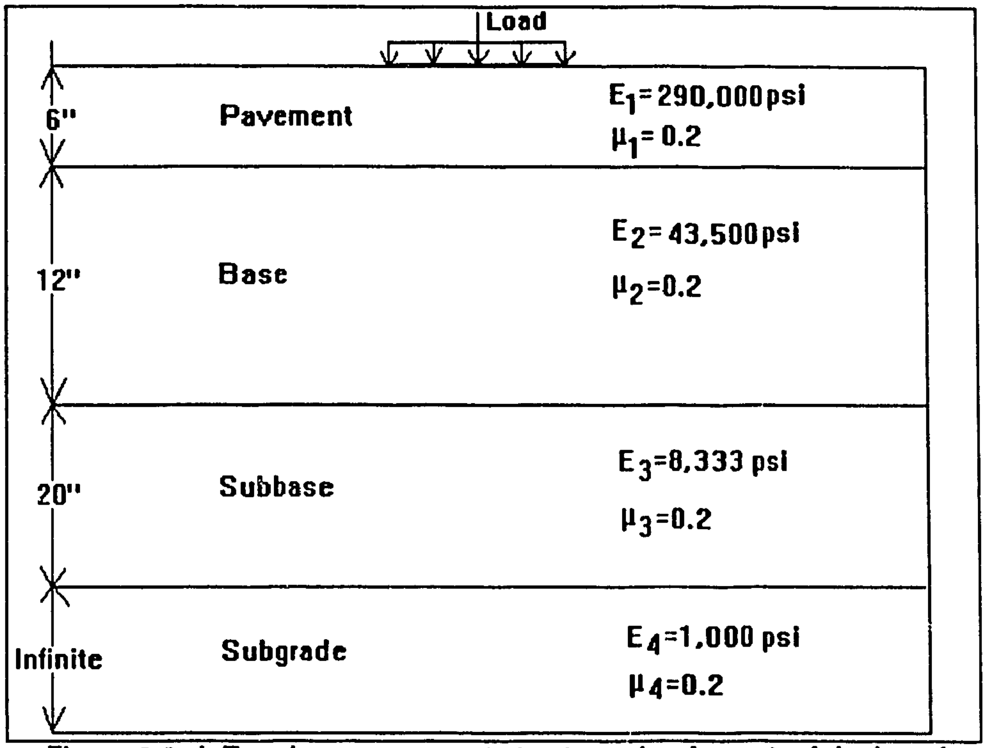


Figure 6.2: A Four-layer pavement structure showing actual designed thicknesses of different layers.
(1-in = 0.0254 m, 1 psi = 6.9 KPa)

Chapter 7

Computer Program

7.1 Introduction

The program for determining the flexible pavement responses (stresses, strains and deflections) by Odemark-Boussinesq analysis are written in Fortran77 language for operation in the IBM compatible personal computer. The flowcharts and explanations of the program are presented in the following sections. Computer program and printout of results are annexed in Appendix-C and D respectively.

7.2 Program capabilities

The program developed for this study is capable of solving the following five different problems as contained in Item 1 through 5.

Item 1. Determination of pavement responses (stresses, strains and deflections etc.) by using Boussinesq's equation when the equivalent thickness h_e of top layers over subgrade is given. For this, load, contact pressure, layer properties (E and μ-values) etc. are required.

Item 2. Determination of pavement responses (stresses, strains and deflections etc.) and equivalent thickness of top layers above subgrade by using Odemark-Boussinesq method. For this, load, contact pressure, layer thicknesses and material properties (E and μ-values) are required.

Item 3. Determination of vertical compressive strains on top of subgrade for different wheel loads and equivalent thicknesses by using Odemark-Boussinesq method. For this, standard load, contact pressure, modulus and Poisson ratio of subgrade material are required. Strain contour charts (loads Vs. Equivalent thicknesses) are prepared from the results thus obtained.

Item 4. Determination of vertical compressive strains on top of subgrade for different subgrade moduli and equivalent thicknesses by using Odemark-Boussinesq's method. Standard wheel load of 9000 lbs. (40 KN), contact pressure and subgrade Poisson's ratio are required. Strain contour charts (subgrade moduli Vs. equivalent thicknesses) are developed from the vertical strains thus obtained.

Item 5. Determination of horizontal tensile strains at the bottom of pavement layer for different thicknesses of pavement (actual). For this, load, contact pressure, Poisson's ratio and modulus of pavement and base layer are required. Different curves (pavement thicknesses Vs. horizontal tensile strains) are drawn to obtain the actual thickness of the pavement layer.

In all the above steps number of layers are to be specified to obtain the required solutions.

7.3 Program Instructions

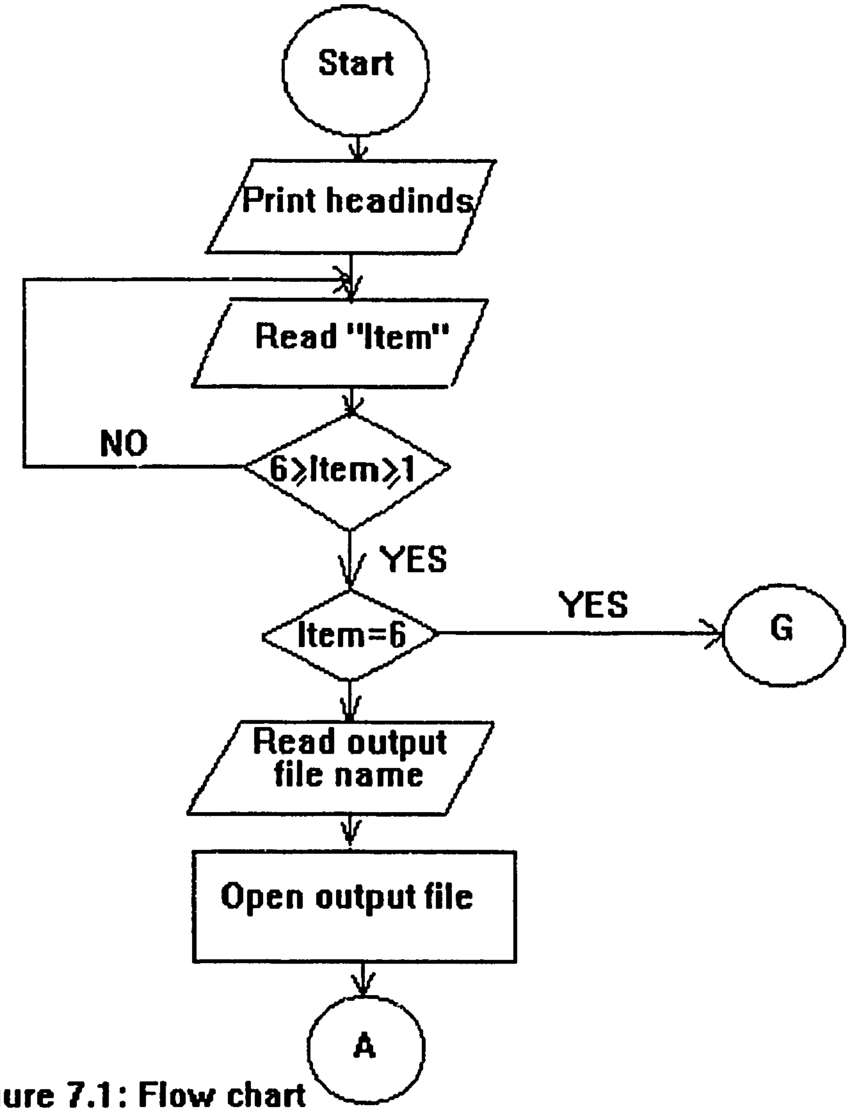
The program starts by entering WATFOR77 PAVEDES and by pressing the return/enter key. Then the program executes by typing "run" and pressing the return/enter key. The menu screen will then be seen as shown in fig C.2 of Appendix C. By typing the required ITEM that needs to be solved and pressing the return/enter key the program will ask for the output file name and input data. As soon as the input data are fed the program will start execution and results will be obtained. ITEM 6 when entered will exit the program.

The program executes with the help of a subroutine "EQUATN" which contains different equations and is called by the main program when required to solve a particular type of problem.

Thus the program allows the user to save the results into a data file on disk.

7.4 Flow chart

The algorithm for developing the computer program used in this study is presented in the flow chart as shown in figure 7.1. The flow chart describes the logic and sequential steps of the program. It is designed to develop and organize for writing the program efficiently. It also makes the reader to understand the program clearly and easily.



Fiaure 7.1: Flow chart

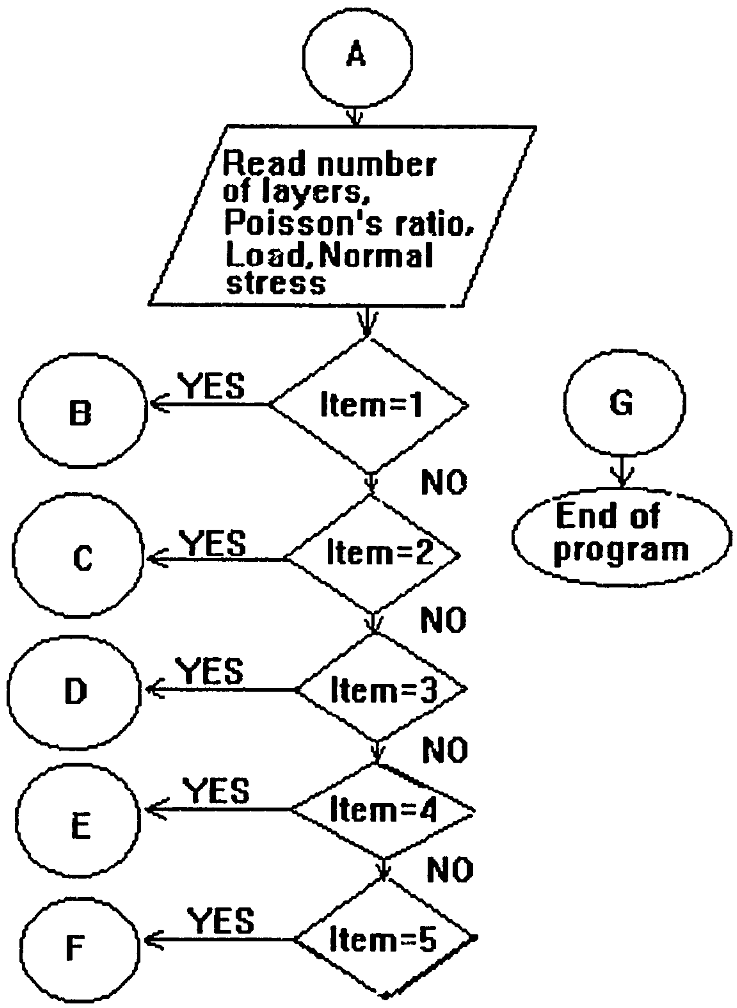
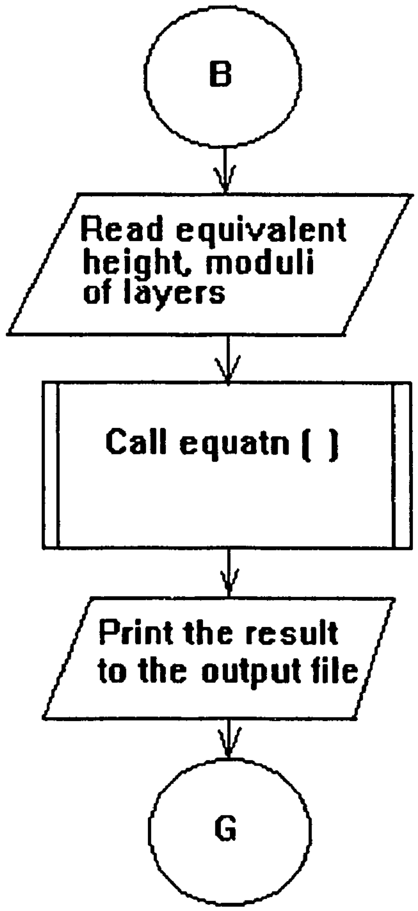

A
Read number of layers, Poisson's ratio, Load, Normal stress
Item=1
YES
NO
B
Item=2
C
Item=3
D
Item=4
E
Item=5
F
G
End of program

Figure:7.1 (a)


B
Read equivalent height, moduli of layers
Call equatn ( )
Print the result to the output file
G
Figure: 7.1(b)

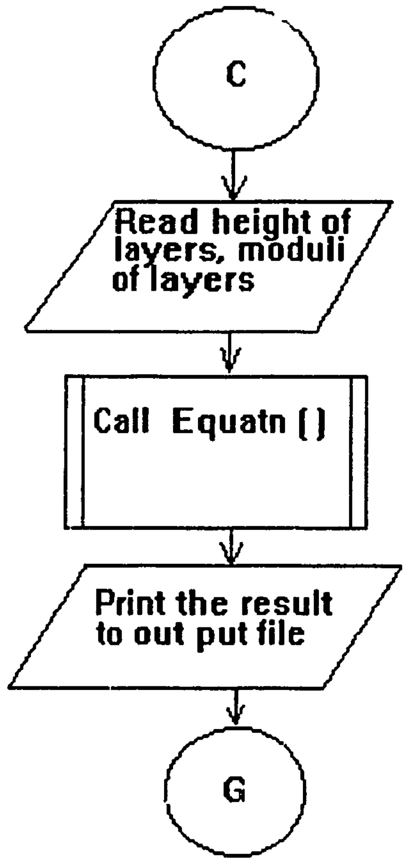
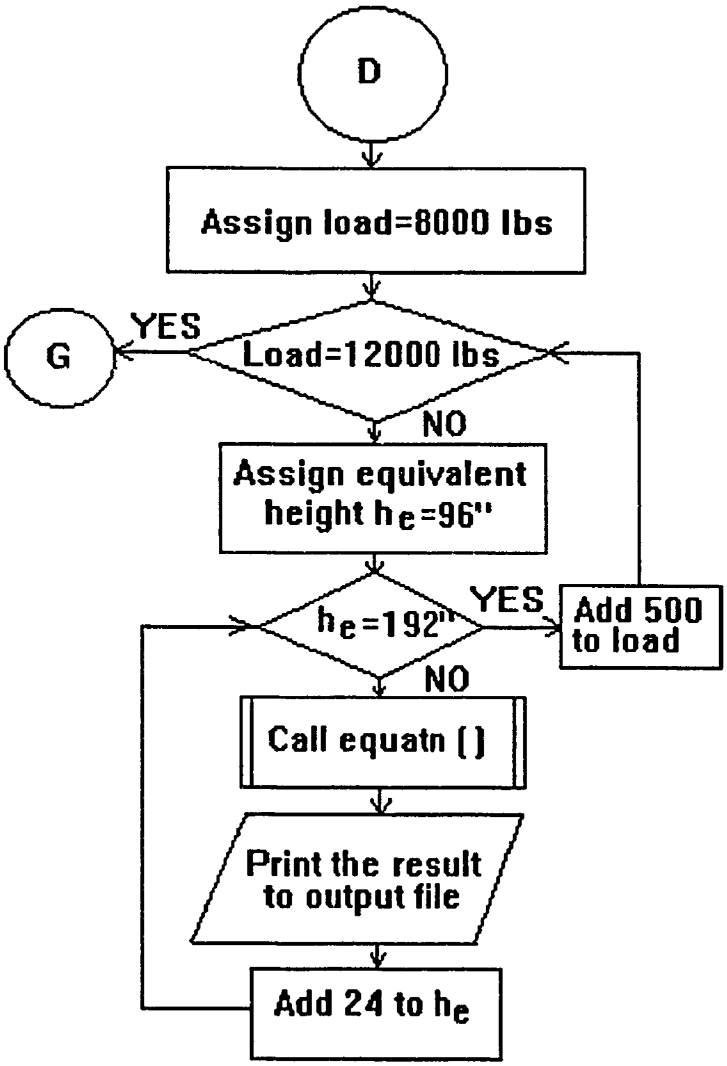
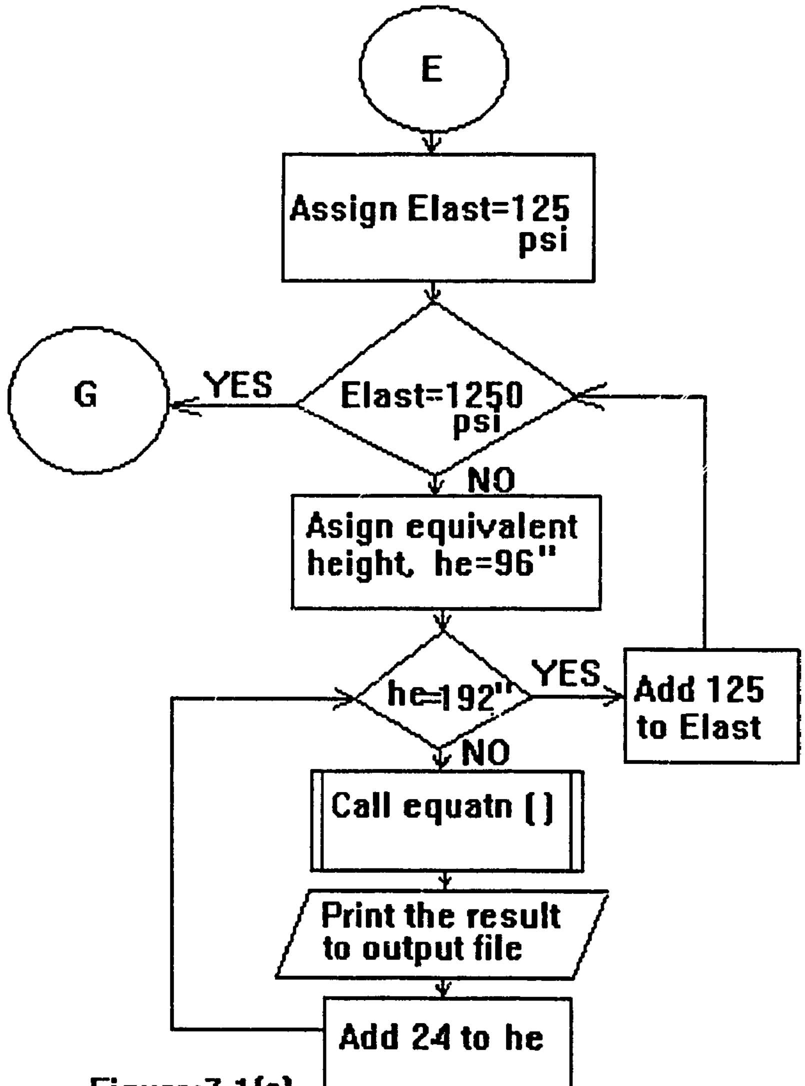

C
Read height of layers, moduli of layers
Call Equatn ()
Print the result to out put file
G

Figure: 7.1 (c)


D
Assign load=8000 lbs
YES
G
Load=12000 lbs
NO
Assign equivalent height h e=96"
YES
h e=192"
Add 500 to load
NO
Call equatn ()
Print the result to output file
Add 24 to he
Figure:7.1 (d)


E
Assign Elast=125 psi
G
YES
Elast=1250 psi
NO
Asign equivalent height, he=96"
he=192"
YES
Add 125 to Elast
NO
Call equatn ()
Print the result to output file
Add 24 to he

Fiqure:7.1(e)

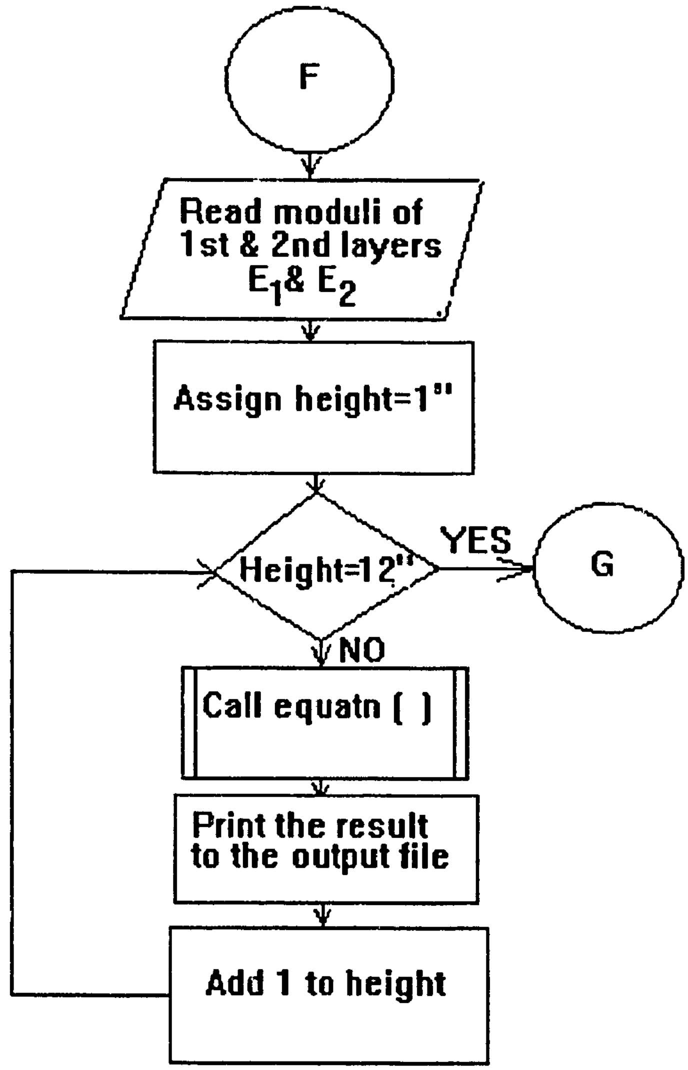

F
Read moduli of
1st & 2nd layers
E1& E2
Assign height=1"
Height=12"
YES
G
NO
Call equatn ( )
Print the result
to the output file
Add 1 to height

Figure:7.1(f)

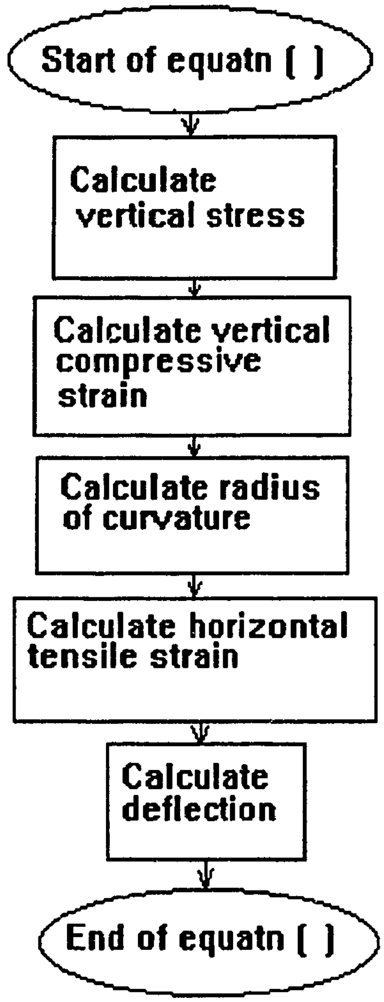

Start of equatn [ ]
Calculate vertical stress
Calculate vertical compressive strain
Calculate radius of curvature
Calculate horizontal tensile strain
Calculate deflection
End of equatn [ ]

Figure:7.1 (g)

Chapter 8

Conclusion

The research work presented in this thesis describes a pavement design method based on Odemark-Boussinesq method and the equations used by the Asphalt Institute. The conclusions obtained from this research work and some suggestions for further study are given below:

8.1 Conclusions

1. Odemark-Boussinesq method can be used to predict vertical compressive strains (ε_c) on the top of the subgrade and horizontal tensile strains (ε_t) at the bottom of the asphalt pavement layer. The subgrade material is assumed to be linear elastic. The repetitive traffic loads maybe considered as a static load of momentary duration since Boussinesq's equations are based on static load.

2. The critical vertical compressive strain (ε_c) on the top of subgrade and horizontal tensile strain (ε_t) at the bottom of the asphalt pavement layer can be determined by Asphalt Institute equations using the design life 18 kips (80 KN) load repetitions due to traffic. These critical strains are used in the proposed design method for determining the thicknesses of different layers.

3. The vertical compressive strain (ε_c) produced at the top of the subgrade is dependant on the wheel load acting on the pavement surface and the equivalent thickness of the

top layers above the subgrade. The strain contour charts developed in this thesis can be used for finding the combination of equivalent thickness and axle load that can produce a given magnitude of vertical compressive strain.

4. The vertical compressive strain (ε_c) produced on the top of subgrade varies with the modulus of the elasticity and Poisson's ratio of the subgrade material and the equivalent thickness of the layers above the subgrade. Strain contour charts developed in this thesis can also be used for finding the required equivalent thickness corresponding to a given elastic modulus (E) and Poisson's ratio (μ) of the subgrade material and the magnitude of the vertical compressive strain.

5. The horizontal tensile strain developed at the bottom of the pavement layer (ε_t) is related to a combination of pavement thickness, moduli of pavement and base layers and their Poisson's ratios. The values of horizontal strains (ε_t) obtained for various combinations of flexible pavement and base moduli and the standard axle load of 18 kips (80 KN) are placed in a graph. This graph is used in the determination of the thickness of flexible pavement.

6. A design method has been proposed to determine the depth at which the RTC-sand subgrade layer is to be located below the pavement surface on which the repetitive axle loads due to traffic act and to determine the thicknesses of various layers (pavement, base and subbase) above the subgrade.

8.2 Topic for further research

Unlike other traditional road building materials, the engineering properties of shredded rubber tire chips, a new kind of material are not well understood. This material is neither fully elastic nor isotropic and its stiffness is low even for moderate loads [11]. An individual rubber particle may have a modulus of elasticity of approximately 7 Mpa (1015 psi), a value that decreases considerably when voids are present in a mass of rubber particles. Typical modulus values for silty soils range from 35 to 150 Mpa, so the rubber particle has a modulus of elasticity 5 to 20 times less than that of a typical subgrade soil [11]. As such further research and investigation for ascertaining the engineering and elastic properties including the behaviour of the shredded rubber tire chips should be thoroughly undertaken so that this material can be used in pavement construction with confidence.

8.3 Environmental Concern

An important question that must be resolved before tire chips are used in some construction applications such as construction of highways etc. is whether they will leach harmful substances. This was the focus of study for the Minnesota Pollution Control Agency and is a component of the University of Wisconsin study [7]. The Minnesota study recommended that the use of waste tires be limited to the unsaturated zone in a roadway designed to limit infiltration of water through the waste tire subgrade. The Wisconsin study concluded that shredded tires pose little or no likelihood of affecting groundwater [5][7]. Both reports suggested the need for additional field studies.

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Appendix-A

Computation of surface deflection

Serial	Title	Page
1.	Odemark-Boussinesq method	A.2
2.	Method of successive approximations	A.4

Figure	Title	Page
A.1	Actual model section	A.3
A.2	Equivalent model section	A.3
A.3	Division of half space into equal layers	A.5

Computation of surface deflections

A two layered box model has been analyzed and surface deflections have been determined by Odemark-Boussinesq method assuming it linear elastic and also by the iterative method of successive approximations with nonlinear elastic assumption. The results when compared show quite close. This confirms that Odemark-Boussinesq method is also capable of analyzing nonlinear behaviour of material property. Detail computation of surface deflection by the above two methods is presented in this Appendix.

Box model is a two layer system consisting of 2ft. (0.6097 m) sand and 3ft. (0.914 m) RTCs and is shown in figure A.1. The equivalent model section is shown in figure A.2.

(A). By Odemark-Boussinesq's method (linear elastic assumption)

Using Odemark's method the equivalent thickness of top layer with respect to the bottom layer

$$h_e = c_f * h_1 * (E_1/E_2)^{1/3}$$

$$= 1.0*24*(8333/257)^{1/3}$$

$$\approx 76" \ (1.93 \text{ m}).$$

(assuming c_f=1.0 for the first interface).

The radius of the loaded area can be obtained as follows

$$a = (P/\sigma_0 * \pi)^{1/2}$$

$$= (8000/58*3.1416)^{1/2}$$

$$= 6.6" \ (0.1676 \text{ m}).$$

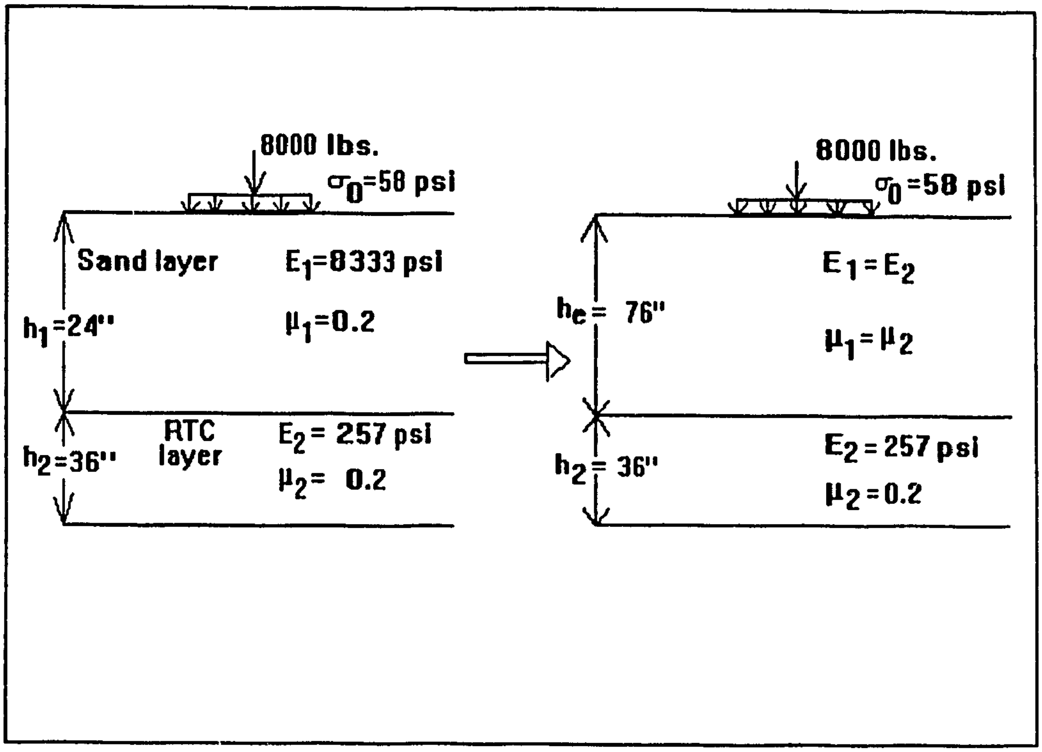

Figure A.1: Actual model section. Figure A.2: Equivalent model section.

(1-in. = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Using Boussinesq's deflection equation, surface deflection is obtained as:

$$d_0 = f*(1-\mu^2)*\sigma_0*a/E_2$$
$$= 2*(1-0.2^2)*58*6.6/257$$
$$= 2.86" \ (0.0726 \text{ m}).$$

where f = 2, for uniformly distributed load,

E_2 = modulus of subgrade layer

and σ_0 = contact pressure.

(B). By iterative method of successive approximation (non-linear elastic assumption)

The equivalent thickness of top layer, h_e =76" (1.93 m) has been divided into four equal number of layers as shown in figure A.3. Then the stresses at midheight of each layer based on Boussinesq's equations have been calculated. From the stresses thus obtained, the elastic modulus E for each layer is determined using equation 2.1. The deformation of each layer, which is the difference in deflection between the top and bottom of each layer based on the given E, can then be obtained. Deformation of all the layers when added together will give the value of surface deflections, d_0.

(1st layer): Vertical stress at depth=9.5"

$$\sigma_z = \sigma_{9.5}=\sigma_0[1-z^3/(a^2+z^2)]^{1.5}$$
$$= 58[1-(9.5)^3/(6.6^2+9.5^2)]^{1.5}$$
$$= 25.868 \text{ psi } (178.36 \text{ KPa}).$$

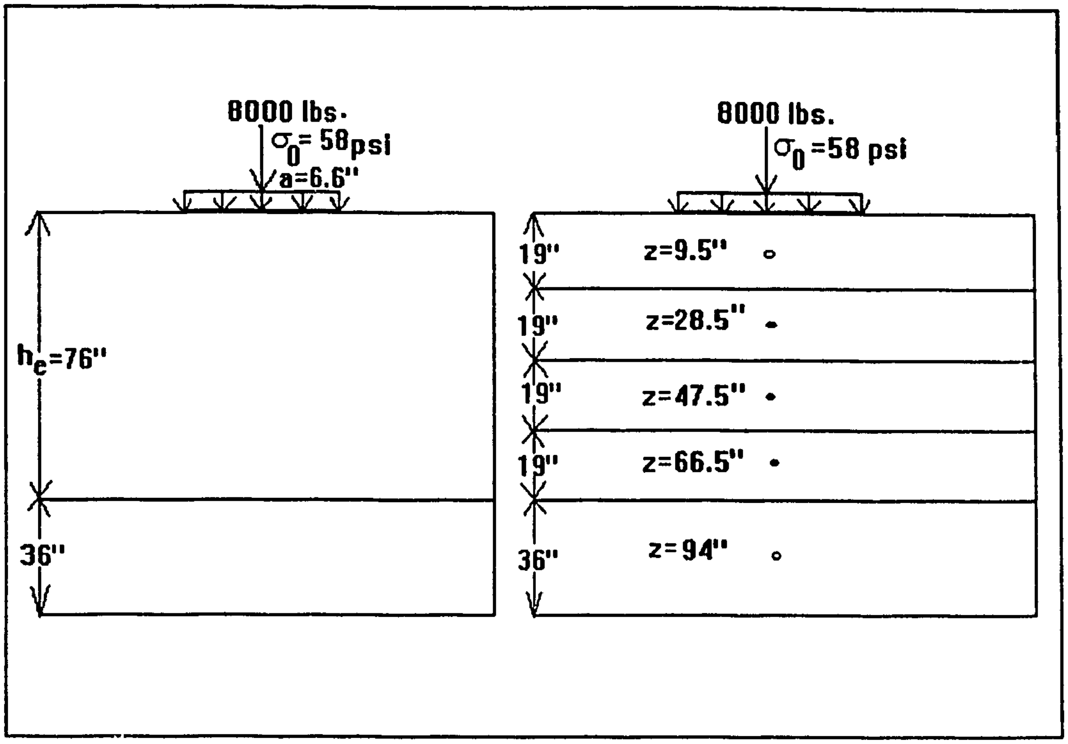

Figure A.3: Division of half space into equal layers.
(1-in. = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Radial and tangential stress at depth=9.5"

σ_r = $\sigma_t = \sigma_0/2[1+2\mu-2(1+\mu)z/(a^2+z^2)^{0.5}+z^3/(a^2+z^2)^{1.5}]$

= $58/2[1+(2*0.2)-2(1+0.2)9.5/(6.6^2+9.5^2)^{0.5}$

$+9.5^3/(6.6^2+9.5^2)^{1.5}]$

= (-)0.493

Stress invariant $\theta=\sigma_z+\sigma_r+\sigma_t+\gamma z(1+2K_0)$

= $25.868-0.493-0.493+35/12^3*9.5(1+2*0.5)$

= 25.267 psi (174.21 KPa).

(assuming unit weight of the material, γ=35 pcf (5498 N/m^3) and coefficient of earth pressure at rest K_0=0.5).

Using equation 2.1

$E_{(1st\ layer)}=E_0(1+\beta\theta)$

= 257(1+0.0104*25.267)

= 324.5 psi (2.237 MPa).

where E_0 = initial subgrade modulus

β = a constant indicating the increase in elastic modulus per unit increase in stress invariant.

Deflection on top of first layer

d_0 = $2(1-\mu^2)\sigma_0*a/E$

= 2*0.96*58*6.6/324.5

= 2.265" (0.057 m).

Deflection at bottom of first layer

$$d_{19} = (1+\mu)\sigma_0 * a/E\{a/(a^2+z^2)^{0.5} + (1-2\mu/a)[(a^2+z^2)^{0.5}-z]\}$$

$$= 1.2*58*6.6/324.5\{6.6/20.1136 + (0.6/6.6)[20.1136-19]\} = 0.607" \ (0.0154 \text{ m})$$

Therefore, deformation of first layer=(2.265-0.607)

= 1.658" (0.042 m).

By similar calculations deformation of second, third, fourth and fifth layer are obtained as 0.2313", 0.1172", 0.0664" and 0.0616" (0.0059, 0.0029, 0.0017 and 0.0015 m) respectively.

Hence total surface deflection

d_0 = $\Sigma$of deformation of all the five layers

= 1.658+0.2313+0.1172+0.0664+0.0616

= 2.14" (0.054 m).

Appendix-B

Strain contour charts

This Appendix contains the remaining Tables of strain values and strain contour charts utilized by the design method which were not included in the body of this thesis. The Table of strains and strain contour charts shown here include:

Table	Title	Page
B.1	Vertical comp. strains for E of subgrade=135 psi, (μ=0.2)	B.3
B.2	Vertical comp. strains for E of subgrade=160 psi, (μ=0.2)	B.4
B.3	Vertical comp. strains for E of subgrade=1780 psi, (μ=0.2)	B.5
B.4	Vertical comp. strains E of subgrade 125-1000 psi, (μ=0.1)	B.6
B.5	Vertical comp. strains E of subgrade 1250-2250 psi, (μ=0.1)	B.7
B.6	Vertical comp. strains E of subgrade 125-1000 psi, (μ=0.3)	B.8
B.7	Vertical comp. strains E of subgrade 1250-2250 psi, (μ=0.3)	B.9
B.8	Vertical comp. strains E of subgrade 125-1000 psi, (μ=0.4)	B.10
B.9	Vertical comp. strains E of subgrade 1250-2250 psi, (μ=0.4)	B.11

Figure	Title	Page
B.1	Strain contour chart E of subgrade 135 psi, μ=0.2	B-12
B.2	Strain contour chart E of subgrade 160 psi, μ=0.2	B.13
B.3	Strain contour chart E of subgrade 1780 psi, μ=0.2	B.14
B.4	Strain contoui chart E=125 psi to 1250 psi, μ=0.1	B.15
B.5	Strain contour chart E=1250 psi to 2250 psi, μ=0.1	B.16
B.6	Strain contour chart E=125 psi to 1250 psi, μ=0.3	B.17
B.7	Strain contour chart E=1250 psi to 2250 psi, μ=0.3	B.18
B.8	Strain contour chart E=125 psi to 1250 psi, μ=0.4	B.19
B.9	Strain contour chart E=1250 psi to 2250 psi, μ=0.4	B.20

(1 psi = 6.9 KPa)

Table B.1: Vertical comp. strains for E of subgrade=135 psi (μ=0.2)

Wheel load (lbs).	Eq.height (he) inch.	Ver. comp. strain. (ε_c).... *10_{-6}
8000	96 120 144 168 192	3181 2038 1416 1041 797
9000	96 120 144 168 192	3577 2292 1593 1171 897
10,000	96 120 144 168 192	3973 2546 1770 1301 996
12,000	96 120 144 168 192	4763 3054 2123 1561 1195

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.2: Vertical comp. strains for E of subgrade=160 psi (μ=0.2)

Wheel load (lbs).	Eq. Height (he) inch.	Ver. comp. strain (ε_c)....*10 ^{6}
8000	96 120 144 168 192	2684 1720 1195 878 672
9000	96 120 144 168 192	3018 1934 1344 988 756
10,000	96 120 144 168 192	3352 2148 1493 1098 840
12,000	96 120 144 168 192	4018 2577 1791 1317 1008

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.3: Vertical comp. strains for E of subgrade=1780 psi (μ =0.2)

Wheel load (lbs).	Eq. height (he) inch.	Ver. comp. strain (ε_c)....$*10^{-6}$
8000	96 120 144 168 192	241 154 107 78 60
9000	96 120 144 168 192	271 173 120 88 68
10,000	96 120 144 168 192	301 193 134 98 75
12,000	96 120 144 168 192	361 231 161 118 90

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.4: Vertical compressive strains for μ=0.1

Elastic modulus of subgrade, E (psi)	Equivalent thickness, (in)	Vertical comp. strain, ε_c.... (*10^{-6})
125	96 120 144 168 192	3814 2444 1699 1249 956
250	92 120 144 168 192	1907 1222 849 624 478
500	96 120 144 168 192	953 611 424 312 239
750	96 120 144 168 192	635 407 283 208 159
1000	96 120 144 168 192	476 305 212 156 119

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.5: Vertical compressive strains for μ=0.1

Elastic modulus of subgrade, E (psi)	Equivalent Thickness, he (inch)	Vertical comp.strain, ε_c....(*10^{-6})
1250	96 120 144 168 192	381 244 169 124 95
1500	96 120 144 168 192	317 203 141 104 79
1750	96 120 144 168 192	272 174 121 89 68
2000	96 120 144 168 192	238 152 106 78 59
2250	96 120 144 168 192	211 135 94 69 53

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.6: Vertical compressive strains for μ=0.3

Elastic modulus of subgrade, E (psi)	Equivalent thickness, he (inch)	Vertical comp. strain, ε_c....(*10^{-6})
125	96	3862
	120	2476
	144	1720
	168	1265
	192	968
250	96	1931
	120	1238
	144	860
	168	632
	192	484
500	96	965
	120	619
	144	430
	168	316
	192	242
750	96	643
	120	412
	144	286
	168	210
	192	161
1000	96	482
	120	309
	144	215
	168	158
	192	121

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 kPa)

Table B.7: Vertical compressive strains for μ=0.3

Elastic modulus of subgrade, E (psi)	Equivalent Thickness, he (inch)	Vertical comp. strain, ε_c.... (*10^{-6})
1250	96 120 144 168 192	386 247 172 126 96
1500	96 120 144 168 192	321 206 143 105 80
1750	96 120 144 168 192	275 176 122 90 69
2000	96 120 144 168 192	241 154 107 79 60
2250	96 120 144 168 192	214 137 95 70 53

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.8: Vertical compressive strains for μ=0.4

Elastic modulus of subgrade, E (psi)	Equivalent Thickness, he (inch)	Vertical comp.strain, ε_c....(*10^{-6})
125	96 120 144 168 192	3812 2444 1698 1248 956
250	96 120 144 168 192	1906 1222 849 624 478
500	96 120 144 168 192	953 611 424 312 239
750	96 120 144 168 192	635 407 283 208 159
1000	96 120 144 168 192	476 305 212 156 119

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

Table B.9: Vertical compressive strain fir μ=0.4

Elastic modulus of subgrade, E (psi)	Equivalent Thickness, he (inch)	Vertical comp. strain, ε_c....(*10^{-6})
1250	96 120 144 168 192	381 244 169 124 95
1500	96 120 144 168 192	317 203 141 104 79
1750	96 120 144 168 192	272 174 121 89 68
2000	96 120 144 168 192	238 152 106 78 59
2250	96 120 144 168 192	211 135 94 69 53

(1" = 0.0254 m, 1 lb. = 4.48 N, 1 psi = 6.9 KPa)

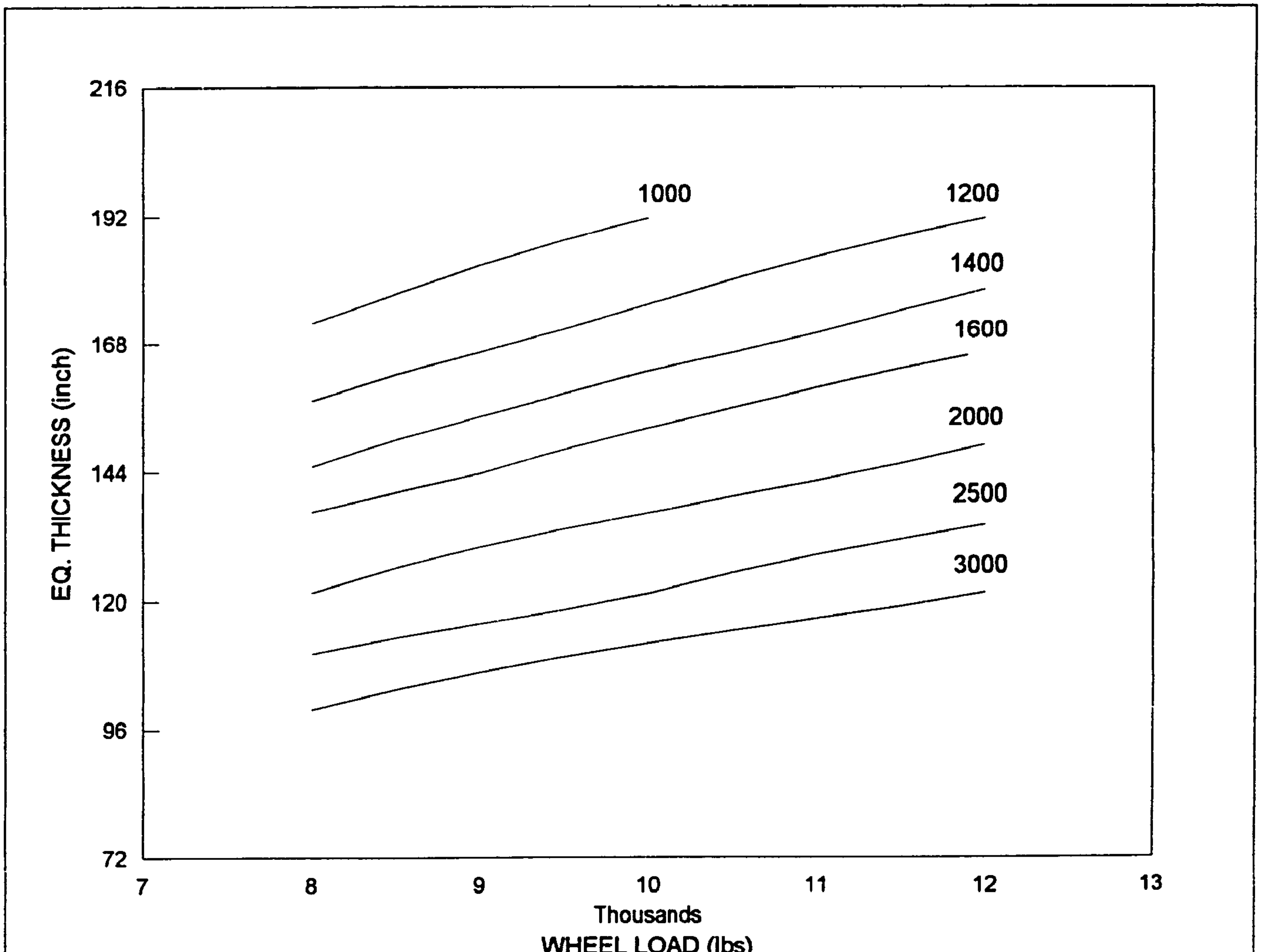

Figure B.1 : Strain Contour Chart (E =135 psi) (u= 0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Wheel Load

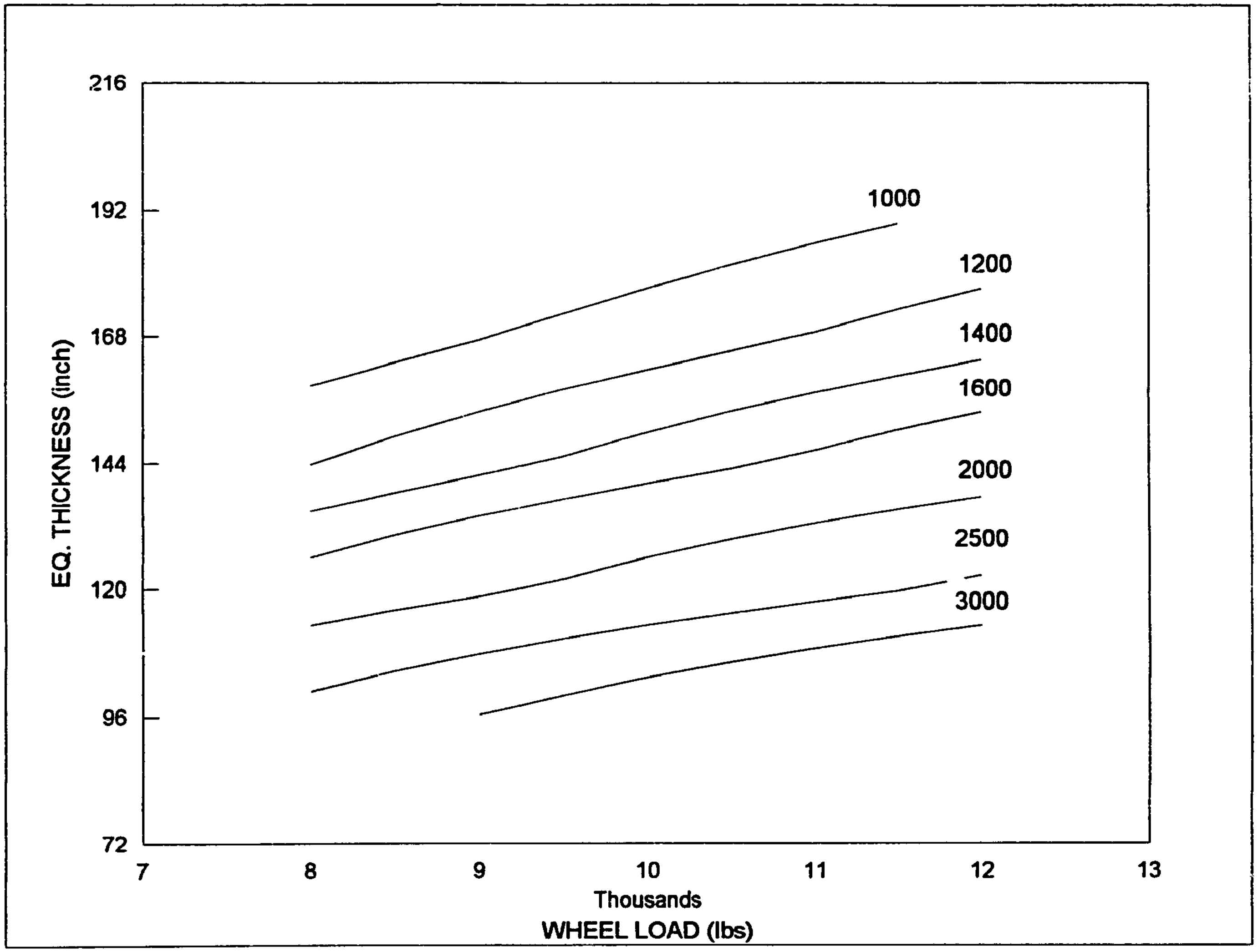

Figure B.2 : Strain Contour Chart (E =160 psi) (u = 0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Wheel Load

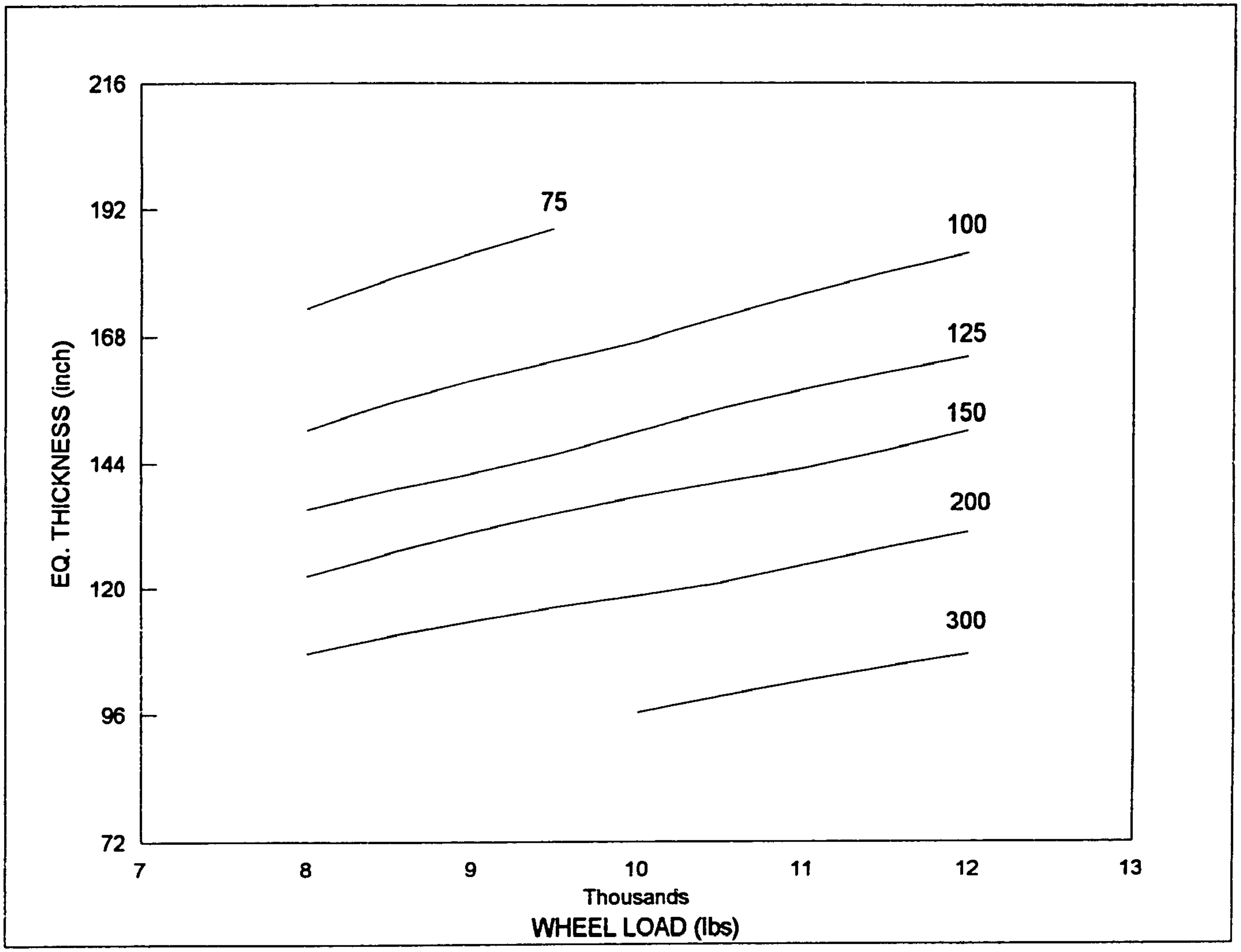

Figure B.3 : Strain Contour Chart (E =1780 psi) (u = 0.2) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Wheel Load

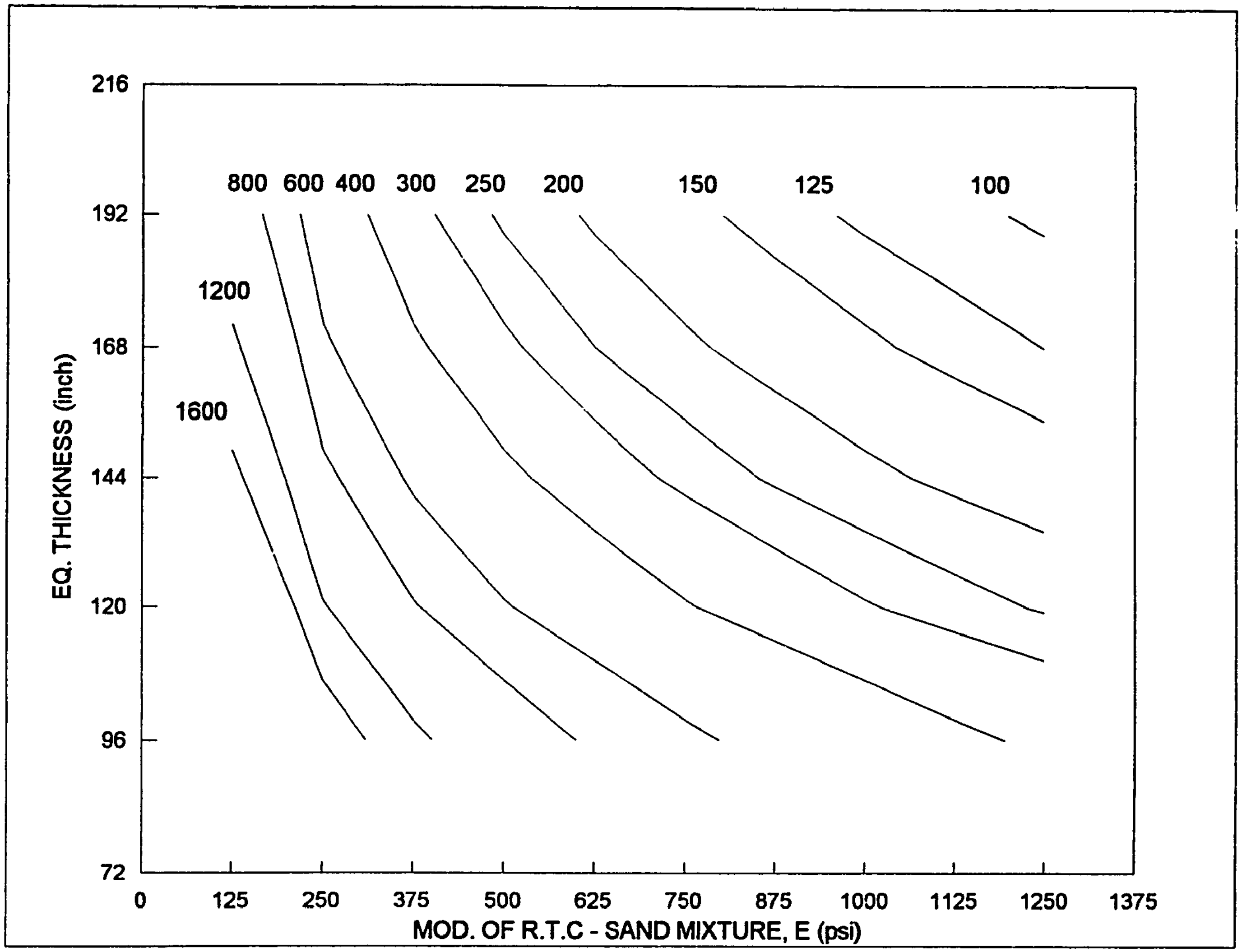

Figure B.4 : Strain Contour Chart (u =0.1) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

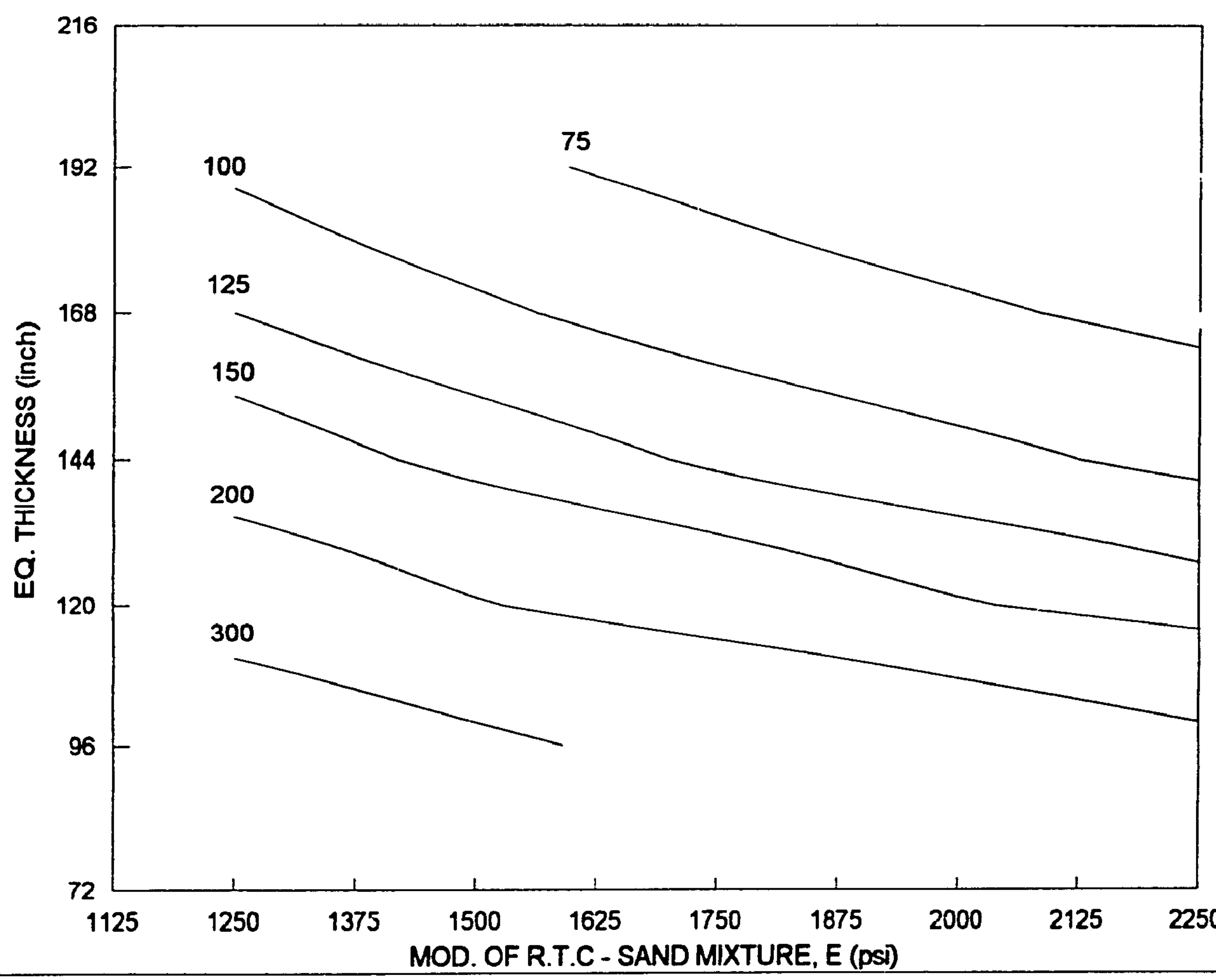

Figure B.5 : Strain Contour Chart (u =0.1) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

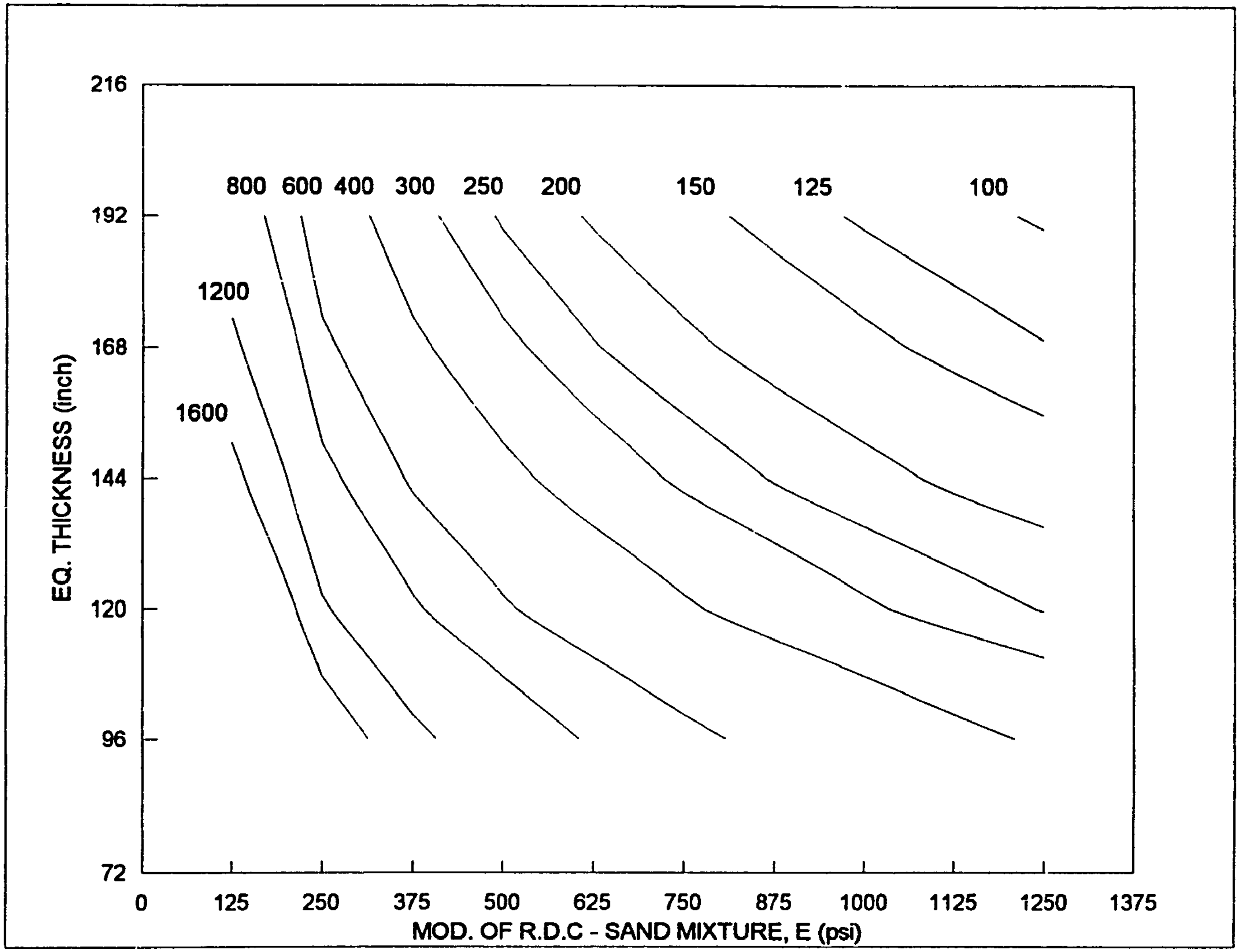

Figure B.6 : Strain Contour Chart (u =0.3) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

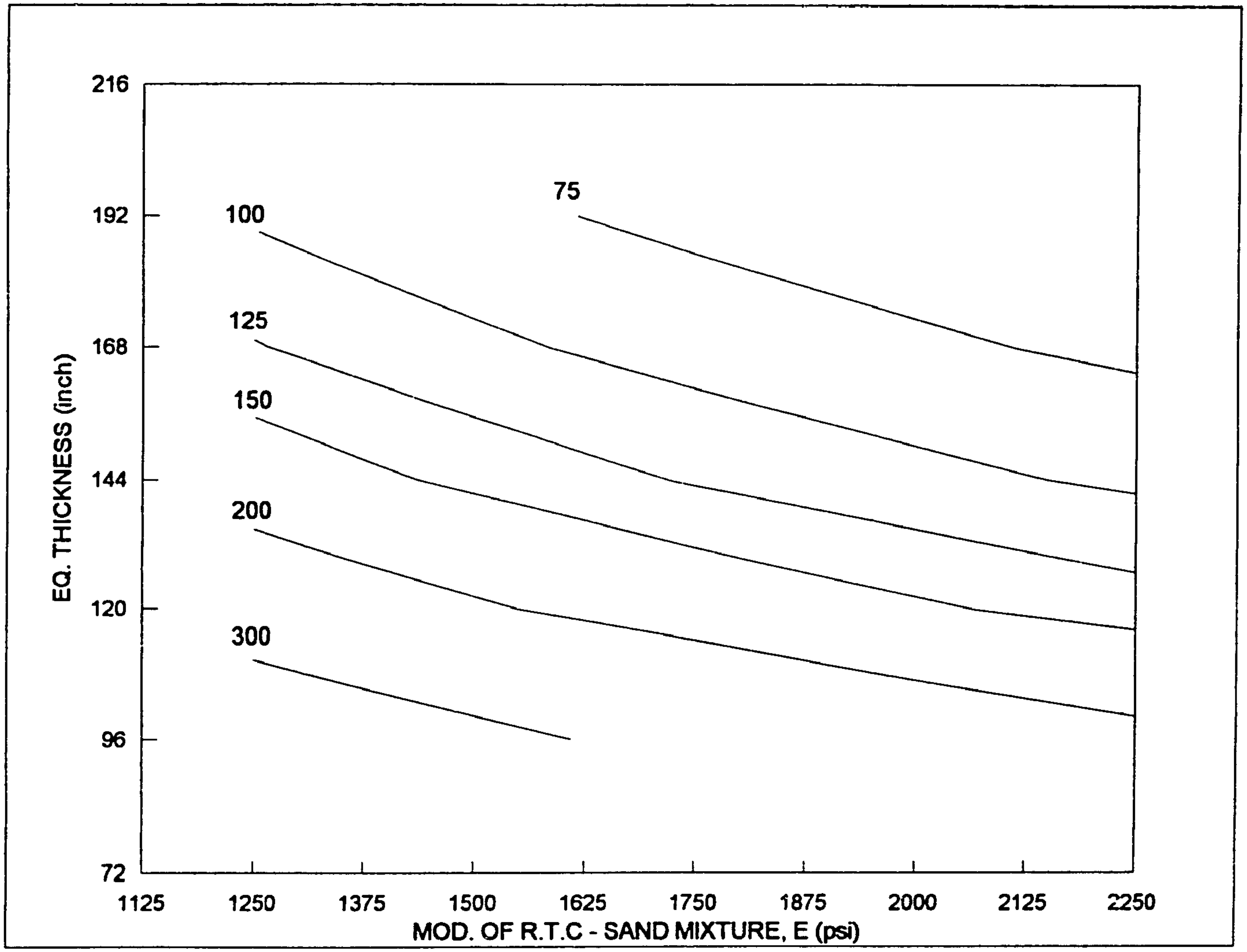

Figure B.7: Strain Contour Chart (u =0.3) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

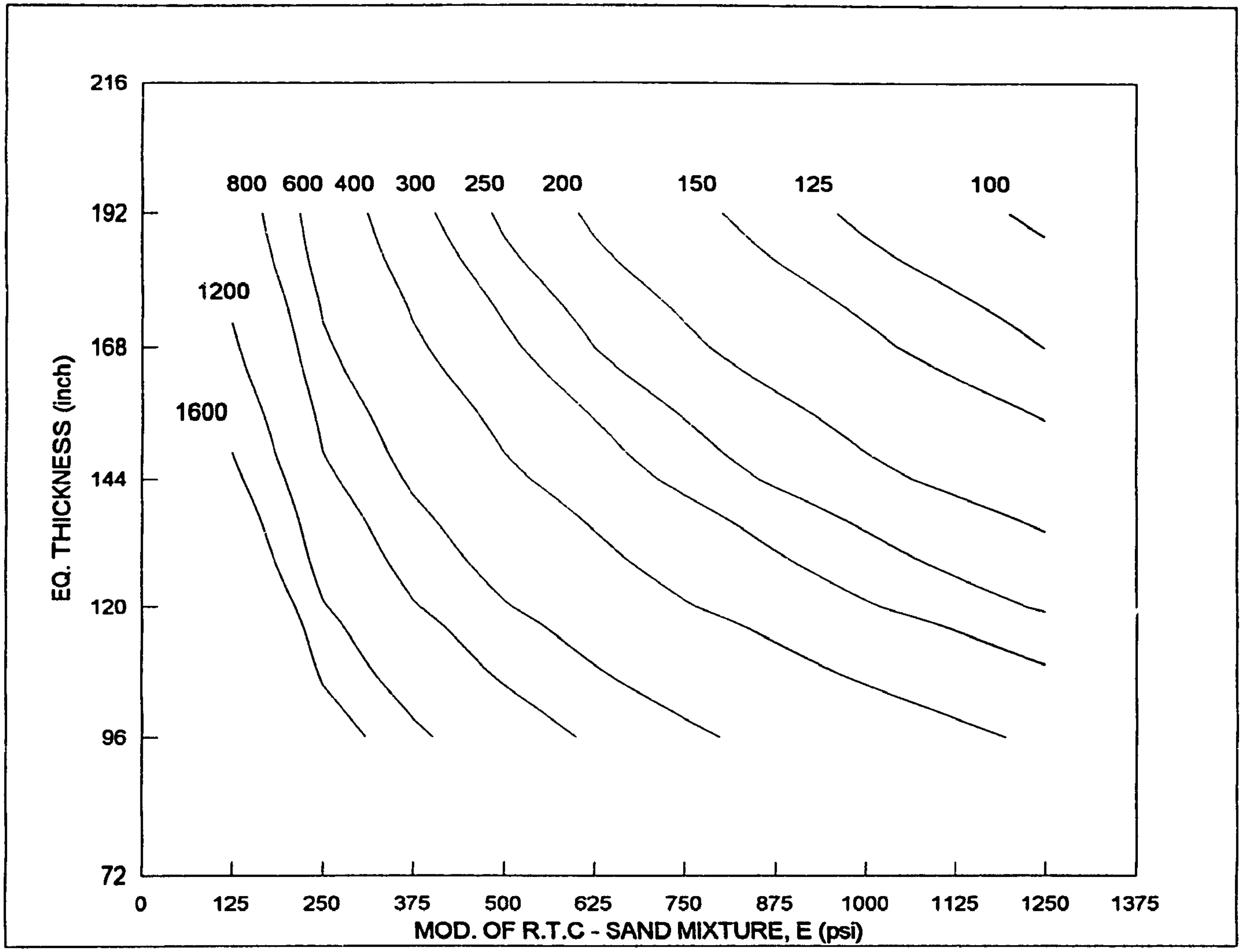

Figure B.8: Strain Contour Chart (u =0.4) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

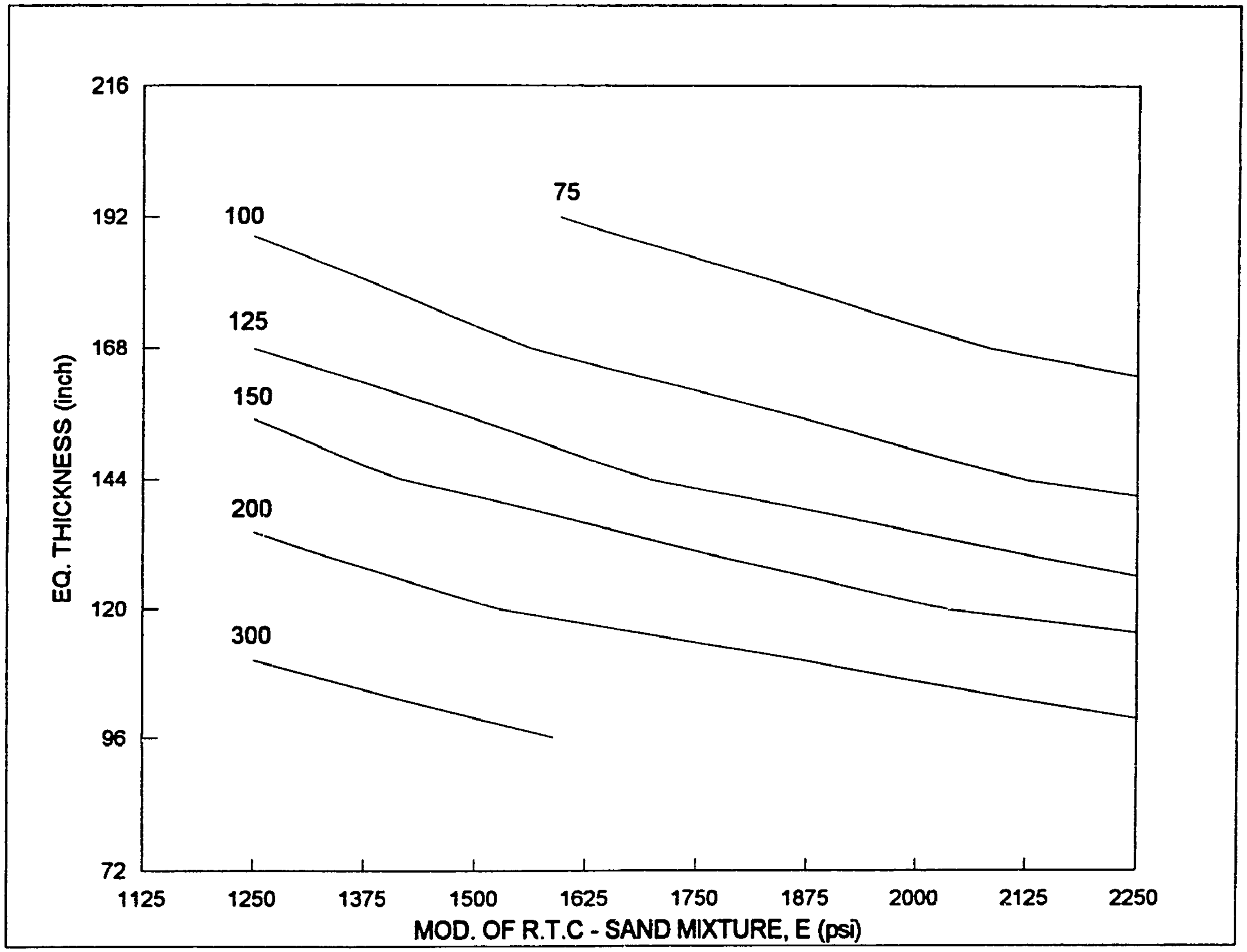

Figure B.9 : Strain Contour Chart (u =0.4) Comp. Strain = ... x10E-6
Equivalent Thickness vs. Moduluos

Appendix C

Computer Program

The computer program developed for the study of this thesis has been written in FORTRAN 77 Language which is shown in this Appendix.

Figure	Title	Page
C.1	Menu Screen	C.2
C.2	Output data file	C.3
C.3	Data input screen	C.4
1.0	Computer program	C.5

```
TYPE OF PROBLEM: WRITE THE VALUE OF ITEM (1-5)
ITEM =  1  MEANS EQ. HEIGHT IS GIVEN
ITEM =  2  MEANS EQ. HEIGHT NEEDS TO BE DETERMINED
ITEM =  3  MEANS PROGRAM FOR STRAIN CURVE WITH LOAD VS.
           EQ. HEIGHT
ITEM =  4  MEANS PROGRAM FOR STRAIN CURVE WITH MOD. OF
           RUBBER TIRE VS. EQ. HEIGHT
ITEM =  5  MEANS PROGRAM FOR HORIZONTAL TENSILE -
           STRAIN (EPST) AT THE BOTTOM OF 1ST LAYER
ITEM =  6  MEANS TO QUIT THE PROGRAM
```

Figure C.1: Menu Screen

```
TYPE OF PROBLEM: WRITE THE VALUE OF ITEM (1-5)
ITEM =  1  MEANS EQ. HEIGHT IS GIVEN
ITEM =  2  MEANS EQ. HEIGHT NEEDS TO BE DETERMINED
ITEM =  3  MEANS PROGRAM FOR STRAIN CURVE WITH LOAD VS.
           EQ. HEIGHT
ITEM =  4  MEANS PROGRAM FOR STRAIN CURVE WITH MOD. OF
           RUBBER TIRE VS. EQ. HEIGHT
ITEM =  5  MEANS PROGRAM FOR HORIZONTAL TENSILE -
           STRAIN(EPST) AT THE BOTTOM OF 1ST LAYER
ITEM =  6  MEANS TO QUIT THE PROGRAM
3
PLEASE ENTER OUTPUT FILE NAME
```

Figure C.2: Output data file

TYPE OF PROBLEM: WRITE THE VALUE OF ITEM (1-5)

ITEM = 1 MEANS EQ. HEIGHT IS GIVEN

IYEM = 2 MEANS EQ. HEIGHT NEEDS TO BE DETERMINED

ITEM = 3 MEANS PROGRAM FOR STRAIN CURVE WITH LOAD VS. EQ. HEIGHT

ITEM = 4 MEANS PROGRAM FOR STRAIN CURVE WITH MOD. OF RUBBER TIRE VS. EQ. HEIGHT

ITEM = 5 MEANS PROGRAM FOR HORIZONTAL TENSILE - STRAIN(EPST) AT THE BOTTOM OF THE 1ST LAYER

ITEM = 6 MEANS TO QUIT THE PROGRAM

3

PLEASE ENTER OUTPUT FILE NAME

'LOAD1.DAT'

INSERT THE VALUE OF THE FOLLOWING VARIABLES

NO. OF LAYERS

4

POISSON RATIO

.2

APPLIED LOAD

9000

NORMAL STRESS-SIGMA 0

100

MODULUS OF ELAST OF LAST LAYER

450 (hold)

Figure C.3 Data input screen

COMPUTER PROGRAM

```
C*********************************
C TYPE OF PROBLEMS:
C*********************************
C
C     ITEM=1 MEANS EQ. HEIGHT IS GIVEN
C     ITEM=2 MEANS EQ. HEIGHT NEED TO BE DETERMINED
C     ITEM=3 MEANS PROGRAM FOR STRAIN CURVE WITH LOAD VS.
C           EQ. HEIGHT
C     ITEM=4 MEANS PROGRAM FOR STRAIN CURVE WITH MOD. OF
C           RUBBER VS. EQ. HEIGHT
C     ITEM=5 MEANS PROGRAM FOR HORIZONTAL TENSILE-STRAIN
C           (EPST) COMPUTATION AT THE BOTTOM OF 1ST LAYER
C     ITEM=6 TO QUIT THE PROGRAM
C     DEFINITION OF VARIABLES USED IN THE PROGRAM
C     NOL= NUMBER OF LAYERS
C     CF = CORRECTION FACTOR
C     MIU= POISSON RATIO
C     P  = APPLIED LOAD(WHEEL LOAD),LBS.
C     SIGO= NORMAL STRESS(CONTACT PRESSURE BETWEEN TIRE & ROAD
C     SURFACE),PSI.
C     H(N) = HEIGHT OF THE LAYERS, H(1)= HEIGHT OF THE 1ST
C        LAYER, ETC.,INCH.
C     HE= EQUIVALENT HEIGHT OF THE LAYERS,INCH.
C     E(N) = MODULUS OF ELASTICITY OF THE LAYERS, E(1)= MODULUS
C        OF ELASTICITY OF 1ST LAYER,PSI.
C     ELAST= MODULUS OF ELASTICITY OF BOTTOMMOST  LAYER,PSI.
```

```
C     A =RADIUS OF THE LOADED AREA,INCH.
C     SIGZ=NORMAL VERTICAL STRESS AT A DEPTH Z BELOW ROAD
C     SURFACE,PSI.
C     EPSZ=VERTICAL COMPRESSIVE STRAIN AT A DEPTH Z BELOW ROAD
C     SURFACE
C     RC =RADIUS OF CURVATURE OF THE PLANE WHERE THE STRAIN IS
C     TO BE FOUND,INCH.
C     EPST=HORIZONTAL TENSILE STRAIN AT A DEPTH Z BELOW ROAD
C     SURFACE
C     DZ = DISPLACEMENT AT A DEPTH Z BELOW ROAD SURFACE,INCH.
C
C *****************************************************************
      REAL    CF,MIU,P,SIGO,H,E,ELAST,SIGZ,EPSZ,RC,EPST,
      DZ,A,HE,PI
      INTEGER NOL,ITEM
      COMMON NOL,CF,MIU,P,SIGO,H,E,ELAST,PI
      DIMENSION H(30), E(30)
      CHARACTER* 30 FILE
      P1=3.14159
      PRINT*, 'TYPE OF PROBLEM: WRITE THE VALUE OF ITEM (1-5)'
      PRINT*, 'ITEM=1 MEANS EQ. HEIGHT IS GIVEN'
      PRINT*, 'ITEM=2 MEANS EQ. HEIGHT NEED TO BE DETERMINED'
      PRINT*, 'ITEM=3 MEANS PROGRAM FOR STRAIN CURVE WITH LOAD
              VS.'
      PRINT*, 'EQ. HEIGHT'
      PRINT*, 'ITEM=4 MEANS PROGRAM FOR STRAIN CURVE WITH MOD.
              OF'
      PRINT*, 'RUBBER VS. EQ. HEIGHT'
```

```
      PRINT*,  'ITEM=5 MEANS PROGRAM FOR HORIZONTAL TENSILE -'
      PRINT*,  'STRAIN(EPST) AT THE BOTTOM OF 1ST LAYER'
      PRINT*,  'ITEM=6 MEANS TO QUIT THE PROGRAM'
5     READ*,ITEM
      IF (ITEM.LT.1.OR.ITEM.GT.6) THEN
         PRINT*,'PLEASE ENTER THE CORRECT VALUE OF ITEM (1-6)'
         GO TO 5
      ELSE
         IF (ITEM.EQ.6) THEN
         PRINT*,'THE PROGRAM IS INTERRUPTED BY THE USER'
         GO TO 180
      ENDIF
      ENDIF
      PRINT*,  'PLEASE ENTER OUTPUT FILE NAME'
      READ*,FILE
      OPEN(UNIT=9,FILE=FILE,STATUS='NEW')
      PRINT*,  'INSERT THE VALUE OF THE FOLLOWING VARIABLES'
      PRINT*,  'NO. OF LAYERS'
      READ*,NOL
      PRINT*,  'POISSON RATIO'
      READ*,  MIU
      PRINT*,  'APPLIED LOAD'
      READ*,  P
      PRINT*,  'NORMAL STRESS-SIGMA 0'
      READ*,  SIGO
      GO TO(1940,1950,1960,1970,1980)ITEM
```

```
1960 PRINT*,'MODULUS OF ELAST OF LAST LAYER'
     READ*,ELAST
     WRITE(9,140)NOL
     WRITE(9,150)MIU
     WRITE(9,160)P
     WRITE(9,15)ELAST
15   FORMAT(3X,'MODULOUS OF THE LAST LAYER',E15.4/)
     WRITE(9,20)
20   FORMAT(64X,'VERTICAL')
     WRITE(9,25)
25   FORMAT(12X,'LOAD, 1BS',16X,'EQ. HEIGHT,
        in',13X,'COMP.STRAIN')
     DO 40 P=8000, 12000, 500
        DO 35 HE= 96,192,24
        CALL EQUATN (HE,A,SIGZ,EPSZ,RC,EPST,DZ)
        WRITE(9,30)P,HE,EPSZ
30      FORMAT(9X,F10.2,16X,F9.2,16X,E15.5)
35      CONTINUE
40   CONTINUE
     GO TO 180
1980 PRINT*,'MOD.OF 1ST LAYER'
     READ*, E(1)
     PRINT*,'MOD. OF 2ND LAYER'
     READ*, E(2)
     WRITE(9,140)NOL
     WRITE(9,150)MIU
     WRITE(9,160)P
     WRITE(9,45)SIGO
```

```
45     FORMAT(3X,'SIGO=',F9.2/)
       WRITE(9,46)E(1)
46     FORMAT(3X,'MODULUS OF PAVEMENT,PSI=',F13.2/)
       WRITE(9,47)E(2)
47     FORMAT(3X,'MODULUS OF BASE,PSI=',F17.2//)
       WRITE(9,48)
48     FORMAT(3X,'THICKNESS  OF  1ST.LAYER,IN',8X,  'HORIZONTAL
       +  TENSILE',1X,'STRAIN,EPST')
       DO 55 HEIGHT=1,12
          H(1)=HEIGHT
          ELAST=E(2)
          A=SQRT(P/(SIGO*PI))
          CHK=H(1)/A*E(1)/E(2)
          IF(CHK.LT.10.0)THEN
          CF=0.96+0.83*A/H(1)*E(2)/E(1)
          WRITE(9,*)CF,CHK
          ELSE
          CF=1.13-0.0565*ALOG((H(1)/A)*(H(1)/A)*E(1)/E(2))
             WRITE(9,*)CF,CHK
             ENDIF
          HE=CF*H(1)*(E(1)/E(2))**(1.0/3.0)
          CALL EQUATN(HE,A,SIGZ,EPSZ,RC,EPST,DZ)
          EPST=HEIGHT/(2.0*RC)
          WRITE(9,50)HEIGHT,EPST
50        FORMAT(12X,F5.2,27X,E15.5)
55     CONTINUE
       GO TO 180
1970   WRITE(9,140)NOL
```

```
      WRITE(9,150)MIU
      WRITE(9,160)P
      WRITE(9,170)SIGO
      WRITE(9,60)
60    FORMAT(14X,'TIRE')
      WRITE(9,65)
65    FORMAT(9X,'MODULOUS, psi',12X,'EQ. HEIGHT, in',
      +  15X,'COMP. STRAIN')
      DO 75 ELAST=125,1250,125
         DO 70 HE= 96,192,24
            CALL EQUATN (HE,A,SIGZ,EPSZ,RC,EPST,DZ)
            WRITE(9,30)ELAST,HE,EPSZ
70       CONTINUE
75    CONTINUE
      GO TO 180
1950  N=1
80    PRINT*, 'HEIGHT OF THE LAYER ', N
      READ*, H(N)
      N=N+1
      IF(N .LE.NOL)GO TO 80
      NM=1
85    PRINT*, 'MODULOUS OF THE LAYER ', NM
      READ*, E(NM)
      NM=NM+1
      IF(NM .LE. NOL) GO TO 85
      ELAST=E(NM-1)
      GO TO 95
1940  PRINT*,'EQUIVALENT HEIGHT'
```

```
      READ*,HE
      NM=1
90    PRINT*,'MODULOUS OF ELASTICITY OF THE LAYER',NM
      READ*, E(NM)
      NM=NM+1
      IF(NM .LE. NOL) GO TO 90
      ELAST=E(NM-1)
      H(NOL)=0.0
C
C     THE FOLLOWINGS ARE THE INPUT DATA TO BE STORED IN THE
C     OUTPUT FILE
95    WRITE(9,140)NOL
      WRITE(9,150)MIU
      WRITE(9,160)P
      WRITE(9,170)SIGO
      IF (ITEM.NE.1) THEN
         DO 105 N=1,NOL
            WRITE(9,100)N,H(N)
100         FORMAT(3X,'HEIGHT OF THE LAYER',I3,F13.5/)
105      CONTINUE
      ENDIF
      DO 115  NM=1, NOL
         WRITE(9,110)NM,E(NM)
110      FORMAT(3X,'MODULUS OF THE LAYER',I3,E13.5/)
115   CONTINUE
      WRITE(9,*)'THE  FOLLOWINGS  ARE  THE  RESULTS  OF  THE
      PROBLEM'
      IF (ITEM.NE.1) THEN
```

```
      N=1
      HE=H(1)*(E(N)/E(N+1))**(1.0/3.0)
      GO TO 125
120      HE=HE*(E(N)/E(N+1))**(1.0/3.0)
125   CF=0.8
      IF (N.EQ.1)CF=1.0
      HE=CF*HE+H(N+1)
      N=N+1
      IF(N.LE.(NOL-1))GO TO 120
      HE=HE-H(NOL)
   ENDIF
   WRITE(9,*)'EQUIVALENT HEIGHT=',HE
   CALL EQUATN (HE,A,SIGZ,EPSZ,RC,EPST,DZ)
   WRITE(9,130)A
130 FORMAT (/3X,'THE VALUE OF A=',E13.5/)
   WRITE(9,*)'EPST=',EPST
   WRITE(9,*)'RC=',RC
   WRITE(9,*)'EPSZ=',EPSZ
   WRITE(9,*)'SIGZ=',SIGZ
   WRITE(9,*)'DZ=',DZ
140 FORMAT(3X, 'NUMBER OF LAYERS=',I5/)
150 FORMAT(3X,'POISSON RATIO=',F5.2/)
160 FORMAT(3X,'APPLIED LOAD=',E13.5/)
170 FORMAT(3X,'NORMAL STRESS=',E13.5/)
180 STOP
   END
   SUBROUTINE EQUATN (HE,A,SIGZ,EPSZ,RC,EPST,DZ)
   REAL CF,MIU,P,SIGO,H,E,ELAST
```

```
      COMMON NOL,CF,MIU,P,SIGO,H,E,ELAST,PI
      DIMENSION H(30), E(30)
      A=SQRT(P/(SIGO*PI))
      SIGZ=SIGO*(1.0-1.0/((1+(A/HE)*(A/HE))**1.5))
EPSZ=((1.0+MIU)*SIGO/ELAST)*((HE/A)/(1.0+(HE/A)*(HE/A))**1.5-
  +   (1.0-2.0*MIU)*((HE/A)/(1.0+(HE/A)*(HE/A))**0.5-1.0))
RC=(ELAST*A/((1.0-MIU*MIU)*SIGO))/(1.0+(1.0+1.5/(1.0-MIU))*
  +   (HE/A)*(HE/A))*(1.0+(HE/A)*(HE/A))**2.5
      EPST=HE/(2.0*RC)
DZ=(1.0+MIU)*SIGO*A/ELAST*(1.0/(1.0+(HE/A)*(HE/A))**0.5+
  +   (1.0-2.0*MIU)*((1.0+(HE/A)*(HE/A))**0.5-HE/A))
      RETURN
      END
```

Appendix D

Sample printouts of result

The computer programs have been used to determine pavement responses (stresses, strains, deflections etc.) in connection with the design method presenred in this thesis. The sample printout for such analysis is presented in this Appendix.

Item	Title	Page
1.	Pavement responses computation when equivalent thickness is given	D.2
2.	Pavement responses computation including equivalent thickness	D.3
3.	Vertical compressive strain computation for different wheel load and equivalent thicknesses	D.4
4.	Vertical compressive strain computation for different subgrade modulus and eq. thicknesses	D.7
5.	Horizontal tensile strain computation for different pavement thicknesses	D.10

Item 1

Determination of pavement responses (stresses, strains, deflections etc.) when equivalent thickness is given (as per programme contained in Item 1).

NUMBER OF LAYERS= 4

POISSON RATIO= 0.20

APPLIED LOAD= 0.90000E+04

NORMAL STRESS= 0.10000E+03

MODULUS OF THE LAYER1	0.29000E+06
MODULUS OF THE LAYER2	0.43500E+05
MODULUS OF THE LAYER3	0.83330E+04
MODULUS OF THE LAYER4	0.10000E+04

THE FOLLOWINGS ARE THE RESULTS OF THE PROBLEM

EQUIVALENT HEIGHT H_e= 120.0000000

VALUE OF A= 0.53524E+01

EPST= 2.7337080E-004

RC= 219482.1000000

EPSZ= 3.0953610E-004

SIGZ= 0.2976894

DZ= .0372098

Item 2

Determination of pavement responses (stresses, strains, deflections etc.) including equivalent thickness (as per programme contained in Item 2)

```
          NUMBER OF LAYERS= 4
          POISSON RATIO= 0.20
          APPLIED LOAD= 0.90000E+04
          NORMAL STRESS= 0.10000E+03
          HEIGHT OF THE LAYER1      6.00000
          HEIGHT OF THE LAYER2      12.00000
          HEIGHT OF THE LAYER3      20.00000
          HEIGHT OF THE LAYER4      24.00000
          MODULUS OF THE LAYER1     0.29000E+06
          MODULUS OF THE LAYER2     0.43500E+05
          MODULUS OF THE LAYER3     0.83330E+04
          MODULUS OF THE LAYER4     0.10000E+04
THE FOLLOWINGS ARE THE RESULTS OF THE PROBLEM
EQUIVALENT HEIGHT= 84.8653400
          THE VALUE OF A= 0.53524E+01
EPST=   0.0005443
RC=     77964.8300000
EPSZ=   0.0006173
SIGZ=   0.5936980
DZ=     0.0525686
```

Item 3

Determination of vertical compressive strains on top of subgrade for different wheel loads and equivalent thicknesses (as per programme contained in Item 3)

NUMBER OF LAYERS= 4

POISSON RATIO= 0.20

APPLIED LOAD= 0.90000E+04

MODULOUS OF THE LAST LAYER 0.1000E+04

VERTICAL LOAD, lbs	EQ. HEIGHT, in.	COMP.STRAIN
8000.00	96.00	0.42947E-03
8000.00	120.00	0.27523E-03
8000.00	144.00	0.19127E-03
8000.00	168.00	0.14058E-03
8000.00	192.00	0.10766E-03
8500.00	96.00	0.45621E-03
8500.00	120.00	0.29238E-03
8500.00	144.00	0.20320E-03
8500.00	168.00	0.14936E-03
8500.00	192.00	0.11439E-03
9000.00	96.00	0.48294E-03
9000.00	120.00	0.30954E-03
9000.00	144.00	0.21513E-03
9000.00	168.00	0.15814E-03
9000.00	192.00	0.12111E-03
9500.00	96.00	0.50965E-03
9500.00	120.00	0.32668E-03
9500.00	144.00	0.22706E-03

VERTICAL LOAD, lbs	EQ. HEIGHT, in.	COMP.STRAIN
9500.00	168.00	0.16691E-03
9500.00	192.00	0.12782E-03
10000.00	96.00	0.53635E-03
10000.00	120.00	0.34383E-03
10000.00	144.00	0.23898E-03
10000.00	168.00	0.17568E-03
10000.00	192.00	0.13455E-03
10500.00	96.00	0.56304E-03
10500.00	120.00	0.36096E-03
10500.00	144.00	0.25090E-03
10500.00	168.00	0.18445E-03
10500.00	192.00	0.14127E-03
11000.00	96.00	0.58972E-03
11000.00	120.00	0.37811E-03
11000.00	144.00	0.26283E-03
11000.00	168.00	0.19322E-03
11000.00	192.00	0.14799E-03
11500.00	96.00	0.61638E-03
11500.00	120.00	0.39523E-03
11500.00	144.00	0.27475E-03
11500.00	168.0C	0.20197E-03
11500.00	192.00	0.15470E-03
12000.00	96.00	0.64303E-03
12000.00	120.00	0.41235E-03

VERTICAL LOAD, lbs	EQ. HEIGHT, in.	COMP.STRAIN
12000.00	144.00	0.28667E-03
12000.00	168.00	0.21075E-03
12000.00	192.00	0.16142E-03

Item 4

Determination of vertical compressive strains on top of subgrade for different modulus of subgrade and equivalent thicknesses (as per programme contained in Item 4)

NUMBER OF LAYERS= 4

POISSON RATIO= 0.20

APPLIED LOAD= 0.90000E+04

NORMAL STRESS= 0.10000E+03

TIRE MODULOUS, psi	EQ. HEIGHT, in	COMP. STRAIN
125.00	96.00	0.38635E-02
125.00	120.00	0.24763E-02
125.00	144.00	0.17210E-02
125.00	168.00	0.12651E-02
125.00	192.00	0.96888E-03
250.00	96.00	0.19317E-02
250.00	120.00	0.12381E-02
250.00	144.00	0.86052E-03
250.00	168.00	0.63255E-03
250.00	192.00	0.48444E-03
375.00	96.00	0.12878E-02
375.00	120.00	0.82543E-03
375.00	144.00	0.57368E-03
375.00	168.00	0.42170E-03
375.00	192.00	0.32296E-03
500.00	96.00	0.96587E-03
500.00	120.00	0.61907E-03
500.00	144.00	0.43026E-03

TIRE MODULOUS, psi	EQ. HEIGHT, in	COMP. STRAIN
500.00	168.00	0.31628E-03
500.00	192.00	0.24222E-03
625.00	96.00	0.77270E-03
625.00	120.00	0.49526E-03
625.00	144.00	0.34421E-03
625.00	168.00	0.25302E-03
625.00	192.00	0.19378E-03
750.00	96.00	0.64391E-03
750.00	120.00	0.41271E-03
750.00	144.00	0.28684E-03
750.00	168.00	0.21085E-03
750.00	192.00	0.16148E-03
875.00	96.00	0.55193E-03
875.00	120.00	0.35376E-03
875.00	144.00	0.24586E-03
875.00	168.00	0.18073E-03
875.00	192.00	0.13841E-03
1000.00	96.00	0.48294E-03
1000.00	120.00	0.30954E-03
1000.00	144.00	0.21513E-03
1000.00	168.00	0.15814E-03
1000.00	192.00	0.12111E-03
1125.00	96.00	0.42928E-03
1125.00	120.00	0.27514E-03
1125.00	144.00	0.19123E-03
1125.00	168.00	0.14057E-03

TIRE MODULOUS, psi	EQ. HEIGHT, in	COMP. STRAIN
1125.00	192.00	0.10765E-03
1250.00	96.00	0.38635E-03
1250.00	120.00	0.24763E-03
1250.00	144.00	0.17210E-03
1250.00	168.00	0.12651E-03
1250.00	192.00	0.96888E-04

Item 5

Determination of horizontal tensile strains at the bottom of pavement layer for different thicknesses of pavemenent (actual) (as per programme contained in Item 5)

NUMBER OF LAYERS= 4

POISSON RATIO= 0.20

APPLIED LOAD= 0.90000E+04

SIGO= 100.00

MODULUS OF PAVEMENT,PSI= 290000.00

MODULUS OF BASE,PSI= 43500.00

THICKNESS OF 1ST.LAYER,IN	HORIZONTAL TENSILE STRAIN,EPST
1.00	0.19717E-03
2.00	0.30866E-03
3.00	0.32425E-03
4.00	0.29344E-03
5.00	0.25087E-03
6.00	0.21051E-03
7.00	0.17625E-03
8.00	0.14829E-03
9.00	0.15097E-03
10.00	0.13150E-03
11.00	0.11554E-03
12.00	0.10236E-03