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An evaluation of fabric reinforcement of the roadway structure is made. The study includes a parametric analysis using layered elastic theory and a series of large scale model tests.

The parametric study analyzes the stresses and strains of roadway structures with a fabric layer between the surface layer and the soil subgrade and compares them to similar systems without fabric. The results show that some benefit results when the fabric is incorporated with a granular surface. No reinforcement is evident when the fabric is incorporated in paved roadways. The analysis, however, does not clearly delineate the benefits; hence, model test results are presented to provide more quantitative data in the indicated range of greatest benefit.

The model tests were performed on a granular roadway structure with and without fabric between the gravel and

the soil subgrade. The fabric was a nonwoven, needle-punched polypropylene (Fibretex 400). The tests were performed in a five foot diameter test pit. Repeated loads of magnitude up to 9000 pounds were applied to simulate traffic. Rut depth and recoverable deflections were measured as functions of the number of load applications.

The effectiveness of the fabric was evaluated with respect to the rate of rut development. A reasonable correlation was found between rutting and the ratio of the vertical stress on the subgrade to the subgrade strength. Measured deflections were compared with values computed by several theories. A finite element method gave good agreement and therefore, was used to estimate stresses in the fabric. The computed fabric stresses indicated if stress on the subgrade was limited to an acceptable value, the factor of safety with respect to fabric strength would be satisfactory.

It is concluded that the common construction fabrics in use today (1977) will not provide significant reinforcement to paved roadways. They may, however, be effective for aggregate surfaced roads on very soft subgrades.

Evaluation of Fabric Reinforcement of the Roadway Structure

by

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a	Radius of load
c	Shear strength
E, E_s	Modulus of elasticity
Mr, M_R	Resilient modulus
P, P_a	Contact pressure
PR	Penetration resistance
R	Radius of load
Z	Thickness of granular base
Δ, δ	Deflection
ε_z	Vertical strain in subgrade
θ	Bulk stress
σ_r	Radial stress
σ_t	Tangential stress
σ_z	Vertical stress
σ_1	Major principal stress
σ_3	Minor principal pressure
ν	Poisson's ratio

EVALUATION OF FABRIC REINFORCEMENT OF THE ROADWAY STRUCTURE

I. INTRODUCTION

1.1 Statement of the Problem

Inserting a fabric layer between the subgrade soil and the granular base or surface coarse has been done successfully to reinforce the roadway structure in poor subgrade areas (12, 30, 46).* This method has been shown to be an economical treatment in many instances. The fabric tends to stabilize the subgrade soil and permit reductions in the required thickness of the roadway structure. However, some investigators have shown that there are conditions where the fabric does not adequately improve stability and in spite of the fabric, the rate of roadway deterioration is still too high.

Fabrics have been used for the stabilization of several types of roads and highways. In the United States, they have most often been used over low bearing capacity subgrades in forest and other low volume roads. Figure 1.1 shows a typical use of a fabric in low volume road construction. In Europe where fabrics have been used for for more than a decade, they have also been incorporated in high type highway and airfield construction.

*Numbers in parentheses refer to items in the Bibliography.

Figure 1.1 Typical use of a fabric in low volume road construction.

The fabrics are believed to perform three functions. First, they act to reinforce the roadway material and help to distribute the load. Second, they separate the overlaying granular materials from the soft subgrade and prevent mixing of the two materials. Finally, the fabric may serve as a drainage path. Most fabrics used in roadway construction have been either polypropylene or polyester non-woven materials. These fabrics have moderate tensile strength, will tolerate quite high elongations without rupture, and are very resistant to decay.

At present, procedures for designing roadways with fabric layers are not well developed. Relatively few detailed studies of fabric stabilized roads have been made; therefore, the behavior under load of roadways with a fabric layer is not clear and the conditions under which fabrics should be used have not been well defined.

1.2 Purpose and Scope

The purpose of this study is to evaluate the effectiveness of fabrics as reinforcement materials for the roadway structure. The scope is limited to the study of the reinforcing effect; the fabric as a separation layer and a drainage layer is excluded. In addition, the study is limited to literature reviews, theoretical analyses and laboratory tests. Field tests are not performed. The range of values of the properties of a wide variety of fabric which might be used for roadway reinforcement are considered theoretically but only Fibretex 400, a nonwoven, needlepunched, spunbounded polypropylene fabric, was tested extensively. One other fabric was used in a limited number of tests for comparison.

1.3 Summary

A review of uses and tests of fabrics is presented in Chapter 2. The review concentrates on the effectiveness of fabrics in the distribution of loads. The filter fabric and the use of fabric to prevent frost penetration are excluded. The literature review has shown that fabrics are effective when the fabric is placed between low bearing capacity subgrades and granular surface courses.

The various theories which might be used to analyse the problem are reviewed in Chapter 3. Specifically considered are Boussenesq, finite element, and elastic layered theories. Vertical stress and strain on the subgrade, radial stress in the fabric and the base are discussed as possible criteria for design. In Chapter 4, a parametric analysis is made of the reinforcing effect of fabric and/or other kinds of material. Elastic layered theory was used for analysis. The purpose of the analysis was to select the conditions for the model tests on fabrics. The systems compared were a three layer roadway structure (surface, fabric and subgrade) and a two layer roadway structure (surface and subgrade). The results showed that when the roadway consists of a granular surface over a soft subgrade, the use of fabric will be most beneficial. Therefore, these were the conditions tested. Pavements and firm subgrades were not investigated further.

Large scale laboratory tests were performed to evaluate the effectiveness of fabric layers under gravel surfaces, study the behavior of fabric reinforced gravel surfaces, and evaluate the theories. Repetitive loads were used to simulate traffic loads. The model tests were limited to conditions of soft to very soft subgrade and a granular surface. The granular material was well graded with a maximum size of 3/4 inch. This gradation was selected because only the reinforcing effects of fabric were to be investigated and the well graded gravel prevented the intrusion of the subgrade into the surface material without the fabric. The subgrade soil was a clayey silt of low plasticity. The repeated load was applied through a rigid steel plate of 12.8 inches diameter. The magnitude of the load was varied from 3,000 to 9,000 pounds.

The testing equipment, preparation of material for the tests and data collection are described in detail in Chapter 5. The test results and discussions of results are in Chapter 6. The results show that the fabric is an effective reinforcement only when the ratio of vertical stress on the subgrade to the strength of subgrade is greater than some critical value.

In Chapter 7, deflections calculated from the theory are compared to deflections measured in the model tests. The finite element method is found to predict the deflections close to the measured values. Therefore, this method was to investigate stresses in the fabric layer.

The evaluation of the effects of fabric reinforcement on the roadway structure is made in Chapter 8. The fabric is likely to be an effective reinforcement when incorporated into low standard roads on soft subgrades subjected to heavy wheel loads.

II. LITERATURE REVIEW OF ROADWAYS INCORPORATING FABRICS

Several investigators have studied the performance of fabric membranes in the roadway structure. Various types of fabric have been used as filter layers and reinforcing materials. The uses of fabric have been developed from field experience and laboratory tests.

2.1 Field Experience and Field Tests of Roadways with Fabric Layers

In England McGown and Ozelton (33) investigated a non-woven fabric. The fabric had a grab strength of 146 pounds (ASTM - 1682), 50 percent elongation at failure, and thickness of 0.03 inch. The test sites were haul roads and the soil had low bearing capacity. At one of the test sites the subgrade soil had an undrained strength of 0.7 psi. The minimum thickness of gravel surfacing was about 16 inches. They indicated that the fabric decreased the rate of rutting. They reported the functions of the fabric as follows: 1 = a separation layer to prevent large quantities of base being lost into the soft subgrade; 2 = a filter permitting drainage into the base without intrusion of fines; and 3 = a tensile member assisting in the redistribution of stresses over weak areas and reducing tensile strain in the base.

In Australia, Ingles and Metcalf (27) reviewed literature from Australia as well as from the other countries. They concluded that the functions of the fabric are the same as indicated by McGown and Ozelton. They suggested that the depth of the fabric layer should be six to nine inches because the maximum radial strain occurs at a depth equal to 1.0 to 1.15 times the diameter of the wheel load. Another literature review presented by Seemel (40) and Dallaire (12) discussed several case histories on the uses of fabric reinforcement in haul road construction over soft subgrades. They did not report strengths of subgrade soils, but indicated that most of the roads with fabric fabric developed ruts at lower rates than those without fabric. In some cases, however, the rutting was still not low enough even with fabric. This may be because the selection of the type of fabric and the thickness of granular surface was based only on experience, without adequate theory.

Recently, Kelsey (30) performed field tests in Southwestern Washington with a non-woven polypropylene fabric (Fibretex) incorporated in gravel surfaced roads. The loading was by gravel trucks with 40,000 to 60,000 pound tandem axle loads. The subgrade was soft clay with high moisture content. He concluded that uses of fabric may be economical, provided that the subgrade is very soft (CBR of 1.5 to 2 and less).

More recently, Visher (46) investigated a low embankment reinforced with fabric on a muskeg subgrade in Southeast Alaska. The muskeg had shearing strengths ranging from 0.35 to 2.4 psi. The fabric was Fibretex which had a strip tensile strength of 70 to 100 pounds per inch of width and 100 to 200 percent elongation at failure. He found that fabric reduced the fill requirements by about 25 percent. The use of fabric was only recommended when the condition of subgrade support is marginal with respect to bearing capacity failure. If the loading is much less than the ultimate bearing capacity, the fabric is of little or no value with respect to reinforcing the fill. He concluded that the fabric helped distribute the load over the subgrade. A theoretical analysis of Visher's test sections was performed by Greenway (18) using non-linear large deflection finite element methods. He concluded that the deflection calculated for construction loading on the embankment agreed with field data reported by Visher, but the presence of fabric had little effect on the predicted deflections in the finite element model.

One test, representing different conditions was performed by the Corps of Engineers (10) in 1968. The fabric used in this test was a neoprene coated nylon with tensile strength of 900 pounds per inch of width and an elongation of 30 percent at failure. This fabric was much stronger than the fabrics investigated by the others. The subgrade material was a highly plastic clay, compacted to a CBR of 4. The base material was the same as the subgrade except that it was compacted to a CBR of 10. Other investigators all have used granular bases. The traffic load was applied to the test section with a 2500 pound single wheel test cart; the contact pressure was 100 psi. The fabric was between the subgrade and the base. They concluded that no significant load distribution benefit was derived from the fabric.

2.2 Model Tests of the Roadway Structure Incorporating Fabrics

Laboratory investigations of the effects of repeated loads on model pavements incorporating a fabric layer have been performed in Japan by Yamanouchi (49,50). Tests were performed to study the improvement of bearing capacity due to a low pressure polyethylene net overlying the subgrade, a soil derived from the weathering of volcanic ash, with a CBR of 1.3 and water content of 115 percent. The material over the net consisted of sand and/or crushed stone under a soil cement surface. This is the only test reported where a stabilized surface layer was used.

There are several significant points from Yamanouchi's tests. The polyethylene net was nearly equivalent to a sand layer six to eight inches thick under the repeated load applied. He indicated that the beneficial effect of the polyethylene net was to prevent soft subgrade soil from intruding into the granular subbase. He did not believe that the restraint effect was great enough to significantly reduce distortion.

The E.I. Du Pont Company (2) has reported a series of tests intended to evaluate the effect of their spunbonded polypropylene, marketed under the name Typar on the effective CBR of soil. The fabric was clamped on top of the soil in a standard CBR mold and the penetration test made directly on top of the fabric. The soil was a clay of medium plasticity. The results showed that the CBR of the system with the fabric was higher than without the fabric. They concluded that when Typar was used over the subgrade the CBR of the system was increased by four.

Barenberg et al. (4) evaluated a soil aggregate system with a heatbonded, heterofilament, nylon-polypropylene fabric (named Mirafi 140) between the granular surface and the subgrade. They used repetitive loads on a model roadway structure. The test was performed in a box 6 x 51 inches with an 18 inch depth. The load was applied on a plate of four by six inches on top of a layer of granular material over a soft subgrade soil. Tests were performed with and without fabric between the subgrade and the granular material. The loading cycle had a duration of ten seconds with the load exerted for one second and a rest period of nine seconds. The fabric which was 0.03

inch thick, had a grab tensile strength of 120 lb (ASTM-1682) and failure elongation of 120 percent. The granular base was an open graded crushed rock with 50 percent smaller than one-half inch. The subgrade had a CBR of 1.0 and less. Systems with the fabric demonstrated a lower rate of permanent deformation than the systems without the fabric. The fabric increased the effective support capacity of the subgrade soil, and allowed approximately twice the stress to be transmitted to the subgrade. In addition, the fabric provided an effective safety factor against the complete failure of the system. Design curves for granular paved roads with and without Mirafi 140 fabric were developed.

2.3 Conclusion

From the reported experience with roadways with fabric layers we can conclude that fabric reinforcement may be beneficial when it is used over soft subgrades; however, the use of fabric was not beneficial under all reported conditions. Also, the criteria for design of roads with fabric have not been well developed and the specific conditions where fabric should be used are not clear.

III. ROADWAY STRUCTURE EVALUATION METHODS

The evaluation and design of roadways include the consideration of traffic loading, material characteristics under dynamic loads, the computation of load-induced stresses and strains and comparisons with the maximum allowable values for various materials in the structure. The purpose of this chapter is to examine and evaluate the current available techniques for predicting responses of the roadway structure to systems incorporating a fabric layer. The scope of the examination is limited to include only failure criteria for the materials in the system, the theoretical analyses for solving the stress and strain relations, and material characterizations.

3.1 Failure Criteria

The materials in the system considered are asphalt-treated materials, granular materials, fabrics and fine grained soils. When a wheel load passes over the roadway structure, the surface will deflect and rebound back, but not to the original position. When many wheels pass, permanent deformations will accumulate to some value due to densification and repetitive non-recoverable plastic strains. As the permanent-deformation increases, rutting will occur and, in some cases, the repetitive wheel load will cause fatigue cracking in the asphalt treated layer.

Therefore, the criteria for the design usually are based on permanent deformation and/or fatigue of the materials in the system.

There are several procedures to design against permanent deformation and fatigue (51). The procedures can be divided into three categories. First, the design procedure can use empirical correlations of excessive deformations which predefine a failure condition of the roadway. An empirical test is used to characterize the materials (19, 32). The second category is based on the excessive deformation related to some predefined failure condition of the roadway, using limiting stress or strain calculated by elastic theory (4,13,38). The third type is based on prediction of accumulated deformation in roadway using laboratory tests of materials in the system (3,51).

The CBR design procedure is an example of the first method. In developing such a procedure several full scale tests must be made with different wheel loads. The effect of size of wheel load cannot be determined in this method except by full scale tests. This method selects the pavement thickness based on some property of the subgrade soil. The requirement for full scale tests eliminates this method from this study. To date, the third method is still under development and should not be used for this investigation. Thus, the method considered will be the second method.

3.1.1 Limiting Stress and Strain Criteria

This design procedure uses elastic theory to analyze the stress and/or strain in roadway structure. The thickness of the roadway is adjusted to reduce the stress and strain to acceptable values. The materials considered are the following:

3.1.1.1 Subgrade Materials

Subgrade materials usually fail by permanent deformation due to repetitive wheel load. The method of limiting subgrade stress has been used to design against permanent deformation.

Rodin (37) proposed a method of predicting permanent deformation of subgrades using subgrade stress criteria. The ability of a clay fill to support a construction plant was studied. He limited the vertical stress on the subgrade soil in terms of shearing strength of the soil. According to Rodin, plastic deformation begins when the vertical stress in the soil is πc where c is the shearing strength of the soil and the rutting will occur when the vertical stress on the subgrade is between πc and the maximum pressure the soil can tolerate without a lateral expulsion of soil from beneath the wheel which is approximately 6.2c. Rodin indicated that an average of these values would produce a rut depth in subgrade of two inches under static condition. This value was conservative for a moving load; therefore, he proposed an allowable vertical subgrade stress of 5c for a moving load. It should be noted that the method of design by limited subgrade stress suggested by Rodin is for a wheel load applied directly on subgrade soil and does not consider the number of load applications.

Recently, Barenberg, et al. (42) applied Rodin's (37) concept to develop a design procedure for granular surface roads incorporating a fabric layer. Model tests were performed in a two-dimensional test tank as explained in Chapter 2. The design methodology for granular surfaced roads with and without Mirafi 140 fabric (heatbonded nylon/polypropylene fabric marketed by Celanese Fibers Company) were developed from the test results shown in Figure 3.1. This figure shows the relationships between the ratio of vertical stress on subgrade (σ_z) calculated by the Boussinesq theory to shearing strength of subgrade soil (c) from vane shear tests and the rut depth. Figure 3.1(a) is the relationship plotted for 10 load applications on granular surface road model. It is shown that the rate of rutting increases rapidly when σ_z/c exceeds 3.3. Figure 3.1(b) is the relationship plotted for 100 load applications to granular surface road with Mirafi 140 fabric; the rate of rutting in this figure increases rapidly when σ_z/c exceeds 6.0c. Therefore, limiting the vertical stress on the subgrade to 3.3c and 6.0c are the

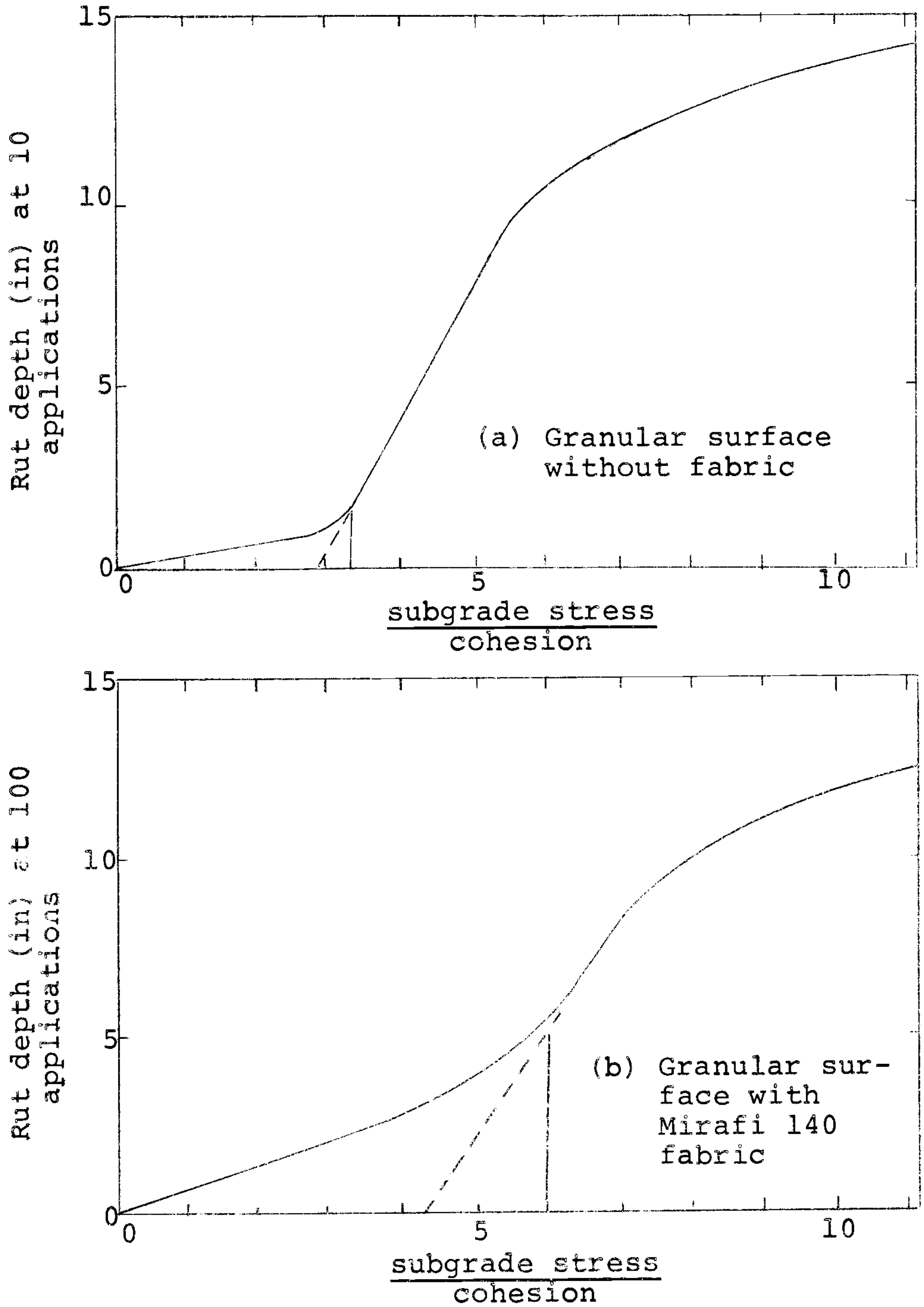


Figure 3.1. Development of design methodology (after Barenberg, et al. (4)).

suggested criteria for a granular surface road and a granular surface road with Mirafi 140, respectively. They further suggested that this design should be limited to a maximum of 10,000 load applications. These criteria were discussed by Barenberg, et al. (4) as follows:

> This design approach is based upon the premise that the allowable subgrade stress has been limited by the depth of aggregate to values which will result in a stabilized roadway with minimal rutting. The number of loads expected over the roadway is not a vitally important factor since the roadway will be stabilized in terms of rut depth. However, it is believed that this premise holds only when the roadway is subjected to number of loading usually expected over a temporary pavement or haul road, and are not the excessive number of loading which are normally expected on permanent roadway installation.

These criteria are empirical and do not consider the number of load applications on the rut depth. Therefore, this should be considered, as well as the fact that the properties of the fabric have not been taken into account. Hence, this method of design may not be applicable for other fabrics.

The procedure of design using limiting subgrade strains has been developed for conventional pavements by Dorman and Metcalf (13). Later, several investigators (47,51) have shown that this method can be used as a standard for design against permanent subgrade deformation. Dorman and Metcalf (13) first developed the relationship between vertical compressive strain and the number of load applications from the several different sections in the AASHO road test. Empirical correlations were used to relate AASHO results. Several agencies have introduced a method based on this approach (47). When using this criteria, it is important to follow the guidelines of the agencies. Recently, Hicks and Finn (25) concluded from the San Diego Test Road Experiment that the limiting criteria for subgrade strain for permanent deformation correlated very well with the field results. The depths of rutting were not indicated in the criteria until recently; Saraf, et al. (38) has summarized from several investigators the relationship between the vertical strain in the subgrade and resulting rutting in the pavement. These criteria are shown in Figure 3.2. The standards are different because of the amount of rutting and the elastic modulus assigned to asphalt concrete layer. The vertical strain concept has been well developed for flexible pavement, but it has not yet been developed for the roadway structure with a fabric layer.

3.1.1.2 Granular Materials

For granular materials, Pell and Brown (36) indicated that most permanent deformation of unbound granular bases occurs during the first loading cycles. Therefore, most of it will happen during the construction period.

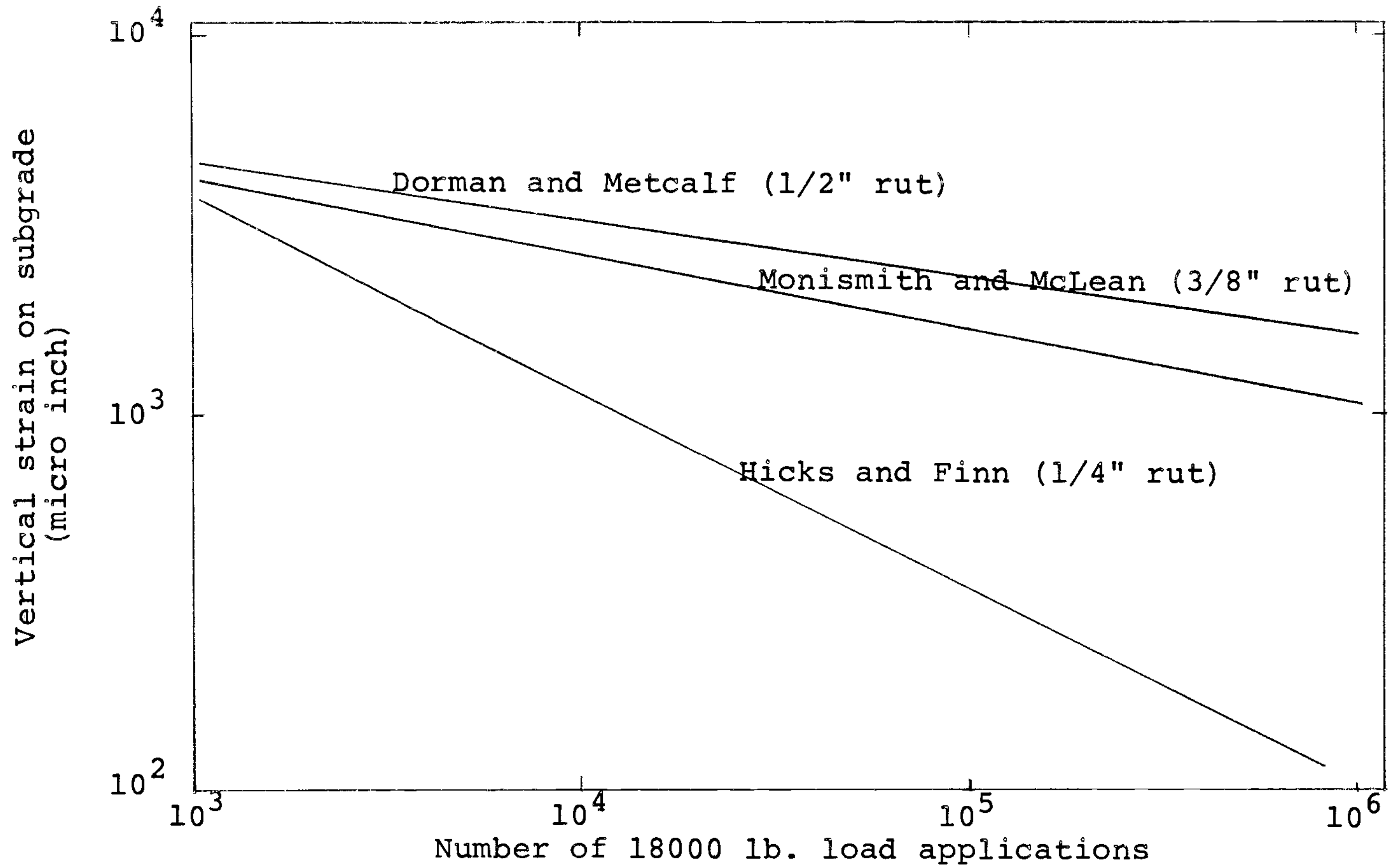


Figure 3.2. Rut depth prediction (after Saraf, et al. (38)).

However, they also indicated that full scale experiments indicated a continuation of small permanent deformation in granular bases during the six month period after the road is open to the traffic.

Brown and Pell (9) further stated that granular bases, when adequately compacted, are stiffer than subgrade soils. Therefore, a radial tensile stress occurs at the bottom of a base when subjected to loading and may cause decompaction of the layer. They also used the concept of Heukelom and Klomp (21) which assumes in the theoretical treatment of the problem that the radial stress at the bottom of granular base will not cause the movement, if it is less than 0.5 to 1.0 times the vertical stress, because interpartical friction will restrain the movement. Furthermore, Brown and Pell (9) indicated that the overburden pressure may add radial tension to the bottom of base. They then suggested that for granular bases the radial tensile stress should not exceed 0.5 times of the vertical stress due to loading plus overburden pressure.

Gerrard, *et al*. (17) indicated that the typical unbound gravel and clay sand base materials have tensile strengths from 5 to 25 psi. The lower value applies to materials with small amounts of binder.

3.1.1.3 Asphalt-Treated Materials

Asphalt-treated materials usually fail by fatigue cracking and the design criterion is tensile strain which occurs at the bottom of the layer. This standard has been well developed and used by several organizations including the Shell Oil Company and the Asphalt Institute. This subject is discussed in detail by Yoder and Witczak (51).

3.1.1.4 Fabric

For the fabric layer, the criteria of failure are not available in the literature. There is the possibility that the criteria may be radial tensile stress, radial tensile strain in the fabric, or friction between the base and the fabric. Later in the study, this will be investigated furtuer.

3.2 Theoretical Analyses

Several theories (11,15,33,47) are available to predict the deflection, stress and strain under load. Each theory has assumptions and limitations. In order to obtain a good prediction of pavement response to load, careful selection of theory should be made. Some of the theories which may be suitable for the problem are discussed below.

3.2.1 Boussinesq Theory

The Boussinesq theory is for homogeneous isotropic and elastic media. It analyzes stress and deflection anywhere in the body. It cannot analyze more than one layer. However, Vesic and Domaschuk (45) indicated from their study of flexible pavement sections at the AASHO road tests that the vertical stress distribution in the layered pavement structure followed the same pattern given by Boussinesq. Other results of this study, concerning the prediction of deflection with the Boussinesq theory, indicated that material properties are very important and must be carefully chosen before accurate prediction of surface deflection can be made.

3.2.2 Layered Elastic Theory

Layered elastic theory was developed by Burmister (11). The theory handles multiple layers of finite thickness supported on an elastic half space with either a perfectly smooth or rough interface. Later, Chevron Oil Company of California (34,47) developed a computer program from the Burmister solution of stress, strain and deflection for any location of a five-layer elastic system with rough interface. The general theory solves the stresses and strains of linear elastic materials, based on the assumption that the modulus of elasticity in tension is equal to the modulus of elasticity in compression. This assumption is very poor for granular material which resists a minimum amount of tension. However, some investigators (21) found that the ratio of the modulus of elasticity of the base to the modulus of elasticity of the subgrade ($E_{base}/E_{subgrade}$) is approximately 2.5. The radial tensile stress is very small when this ratio is used in the calculation. The ratio is based on insitu investigations using a wave propagation technique (21). It was found from this study that the ratio of the base modulus to the subgrade modulus ranges from approximately 1.5 to 2.5 for general subgrade and 5 for very soft subgrade, and the modulus of elasticity of granular base depends on the support condition.

Later, Kasain Chuk (29) developed a layered elastic computer program with iteration which characterized the modulus of elasticity of granular materials by the relationship:

$$Mr = K1\theta^{K2}$$

where: Mr = resilient modulus

K1,K2 = constants obtained from laboratory test

θ = bulk stress.

By this relation, the modulus of elasticity is small when tension exists. That the modulus of elasticity of granular materials depends on the state of stress has been confirmed by several investigators. This program also handles the modulus of cohesive soils which is found to be dependent on the deviator stress. The modulus of the subgrade is interpolated from the input modulus-deviator stress relationship. The description of the programs and the limitations and assumptions are explained elsewhere (24). One of the major assumptions which is not applied very well to the roadway structure with fabric is the rough interface (continuity of interface) between layers. This assumption may create an error in predicting the deflection of the embankment as indicated by Greenway (18).

Layered elastic theory has been used successfully in predicting the response of the roadway structure. Brown and Pell (8) analyzed a model test section consisting of a granular surface and soil subgrade using linear, layered elastic theory. They found that elastic theory predicted vertical normal and maximum shearing stresses and maximum surface deflection satisfactorily. Seed, et al. (39) also used layered elastic theory to predict the response of a layered system consisting of asphalt concrete, granular base, and clay subgrade. Later Hicks (23), Hicks and Finn (25), Hicks and Monosmith (26) used the layered elastic theory with iteration to predict the responses of pavement sections. They indicated that the typical ratio of predicted surface elastic deflection to measured deflection ranged from 0.4 to 1.4.

3.2.3 Finite Element Theory

The finite element method is a numerical analysis technique performed with the aid of a computer. The basic concept is the idealization of the actual continuum as an assemblage of discrete structure elements, interconnected at nodal points. For structures that are geometrically axisymetric, the nodes are actually circles and are called nodal circles.

A finite element program was modified for pavements by Duncan, et al. (15) from an axisymmetric program developed by Wilson (48). The program utilizes an element bounded by horizontal and vertical lines, applies a surface load as a series of increments, handles nonlinear materials. Poisson's ratio is input as a constant for each material and the resilient modulus may also be specified for each material. The material may be considered to be linear elastic with constant modulus or with temperature dependent moduli. Values of temperature and the associated modulus may be input for various points. The program interpolates for the modulus between specified points or the modulus may be input as a function of bulk stress or confining stress ($Mr = K1\theta^{K2}$ or $Mr = K1\sigma_3^{K2}$). The modulus may also be defined as a function of deviator stress for subgrade materials.

$$Mr = K2 + K3\ [K1 - (\sigma_1-\sigma_3)] \quad K1 > (\sigma_1-\sigma_3)$$

$$Mr = K2 + K4\ [(\sigma_1-\sigma_3) - K1] \quad K1 < (\sigma_1-\sigma_3)$$

The three methods of analysis mentioned earlier have both advantages and disadvantages. Boussinesq is simple to use; the vertical stress distribution calculated by Boussinesq is close to the field value, but it is limited to one layer and cannot handle fabric tension.

Layered analysis by the computer program developed by the Chevron Company (CHEV-5L) is more accurate than Boussinesq. It can consider layers of different materials which are linear elastic. Minimum computer time is required compared to the other computer program, but it cannot handle non-linear behavior while layered elastic theory with iteration can. This program takes more computer time.

The finite element method has an advantage over the above methods in that it can consider non-linear materials. The modulus of elasticity may vary in each element in both the vertical and radial direction and may depend on the state of stress in each element. This method requires more computer time than the others.

3.3 Material Characterizations

Reasonably good predictions of pavement response to load can be obtained, provided material properties are carefully selected. When the layered elastic theory and the finite element methods calculate stress and strain, the two material properties used are the modulus of elasticity, usually in terms of resilient deformation of material, and

Poisson's ratio. These properties are also needed when the Boussinesq theory is used to analyze the deflection. Therefore, the material properties discussed will concern modulus of elasticity and Poisson's ratio.

3.3.1 Asphalt-Treated Materials

The load deformation response of asphalt-treated materials varies depending on temperature and the rate of loading. In general, as the temperature increases and the rate of loading decreases, the stiffness, and modulus of elasticity decrease.

Reported values (51) for the modulus of asphalt mixtures under normal conditions range from 150,000 to 1,000,000 psi depending on temperature, rate of loading and relative quality of mixture. Poisson's ratio ranges from 0.3 to 0.4 for asphalt-treated aggregate.

3.3.2 Granular Materials

Several researchers (15,23,41) have shown that the modulus of elasticity of untreated granular materials is significantly influenced by the state of stress. It is affected more by confining pressure and less by the magnitude of deviater stress. The modulus of elasticity is related to stress as follow:

$$Mr = K1\theta^{K2}$$

or

$$Mr = K1\sigma_3^{K2}$$

where: K1,K2 = constants from repeated load triaxial tests

σ_3, θ = confining pressure and the sum of the principal stresses

In addition, the resilient modulus is affected by stress history (23), duration of load and frequency of load application (39,42), aggregate type and gradation (23), density (23), and degree of saturation (20). However, such factors are less significant than the state of stress. Table 3.1 summarizes the resilient modulus data for granular materials.

Another approach of determining the resilient response of granular materials is empirical correlation obtained from insitu investigations using wave propagation techniques. It is shown that the modulus of elasticity is a function of the support condition. The ratio of the modulus of elasticity of the base to the subgrade is normally 1.5 to 2.5 but may be as high as 5 for very soft soil. The relations used by several agencies are shown in Table 3.2.

Typical values of Poisson's ratio for granular base materials suggested by various organizations range from 0.45 to 0.5 (51). Hicks (23) found that Poisson's ratio is a function of the principal stress ratio:

Table 3.1. Resilient modulus of granular material.

Researcher	Material	Resilient Modulus (psi)	Comments
1. Seed & Chan	Silty sand	21,300 to 27,300	Varied frequency and duration of load
2. Haynes & Yoder	Gravel and crushed stone	28,000 to 63,000	Varied moisture content and gradation
3. Biarez	Rounded aggregate	16,700 to 54,500	Varied stress level and void ratio
4. Trollope, Lee and Morris	Poorly graded dry sand	35,000 to 95,000	Varied stress levels
5. Dunlap	Well graded aggregate	30,000 to 160,000	Varied stress levels
6. Mitry	Dry gravel	7,000 $\sigma_3^{0.55}$ to 1,900 $\theta^{.61}$	Varied stress levels
7. Schiffley	Crushed gravel	13,000 $\sigma_3^{0.5}$ to 9,000 $\sigma_3^{0.5}$	Varied moisture content
8. Kasianchuk	Aggregate base	3,830 $\theta^{.53}$	Varied stress levels
	Aggregate subbase	2,900 $\theta^{.47}$	
9. Hicks & Finn	Aggregate base	5,400 $\theta^{.50}$ to 21,000 $\theta^{.5}$	Varied moisture content
10. Browns & Pell	Aggregate base	2,040 $\theta^{0.57}$	Calculated from insitu tests
11. Smith & Nair	Aggregate base	2,000 $\theta^{0.6}$ to 5,000 $\theta^{0.6}$	Extremes from all experiments

Table 3.2. Granular base-subgrade modular ratios.

Agency	K = Modular Ratio for $E_{subgrade}$ Given				
	3000	6000	12,000	20,000	30,000
Shell Oil Company	3.5	2.4	1.9	1.8	1.7
The Asphalt Institute	4.8	2.7	1.8	1.6	1.5
Kentucky Highway Department					
E_{AC} = 150,000 psi	4.6	3.5	2.7	2.2	1.9
270,000 psi	4.2	3.4	2.7	2.3	2.0
600,000 psi	3.8	3.2	2.7	2.4	2.2
1,800,000 psi	3.6	3.1	2.7	2.5	2.3

$E_{base} = KE_{subgrade}$

$$\nu = A_0 + A_1 (\sigma_1/\sigma_3) + A_2 (\sigma_1/\sigma_3)^2 + A_3 (\sigma_1/\sigma_3)^2$$

Allen (3) indicates that the constant confining pressure test data greatly overestimates Poisson's ratio due to the anisotropic nature of material and the greater amount of volume change which is observed in this type of test. However, he indicates that the range 0.35 to 0.40 adequately represents the parameter for pavement analysis. Smith and Nair (41) concluded from a double cycle stress test that Poisson's ratio did not depend on principal stress ratio. Poisson's ratio from their tests were between 0.3 and 0.4.

3.3.3 Subgrade Materials

The modulus of elasticity of a fine grained soil depends on soil type, moisture, density and state of stress. The most significant effect is the axial deviator stress. At low stress levels, the resilient modulus decreases rapidly with increasing values of the deviator stress; as the deviator stress increases further, there is only a slight increase in resilient modulus.

Heukelom and Foster (22) have proposed a relation between the dynamic modulus and CBR value based on investigations using wave propagation techniques. The factor varied between about 700 and 2500. They suggested that the average value for the correlation be used and recommend

$$E = 1500 \times CBR$$

where: E is in psi.

When this method is used extreme caution should be taken because the relations obtained are empirical and there is considerable variation in the data.

The Poisson's ratio of subgrades is usually from 0.45 to 0.5.

3.3.4 Fabric Materials

None of the investigations in the literature have characterized the fabric materials in terms of modulus of elasticity and Poisson's ratio. The mechanical properties of the fabrics are usually given as breaking force and elongation at failure. Some typical properties as given by the suppliers are presented in Table 3.3. The breaking load tests are divided into two methods: grab test and strip test. In the grab test, part of the specimen is gripped in clamps. The specimen width is usually four inches and the width of the clamps is one inch. In the strip test, the full width of the specimen is gripped in the clamps. The test conditions are room temperature and a dry specimen, which are not the conditions expected in the field. However, the effect of temperature has been studied by Mark (1). He performed a tensile strength test on Polyfelt TS 300 fabric, using the ASTM-1682 standard

Table 3.3. Properties of some common fabrics as given by their distributors.

Type	Fibretex 400	Bidim C34	Mirafi 140	Typar 3401	Polyfelt TS 300
Composition	Polypropylene	Polyester	Nylon and polypropylene	Polypropylene	Polypropylene
Distributor	Crown Zellerbach Company	Mosanto Textile Company	Celanese Fiber Marketing Company	E. I. Dupont Company	Advance Construction Specialties Company
Thickness (inches)	.165	.109	.03	.015	.127
Grab Tensile Strength (lb) ASTM D-1682	290	234	120	130	227.74
Failure elongation (%)	150	50	120	65	101.2
Weight O_z/yd^2	12.4	9.2	4.1	4.0	7.7
(gm/m^2)	(420)	(312)	(140)	(135)	(261)

method. He found that under the frozen state at -50°C, the breaking strength was the same as determined for standard conditions; however, the elongation of failure decreased from 101 percent at standard conditions to 51 percent at -50°C. The dynamic modulus and Poisson ratio of fabric is not available. Therefore, this behavior and resilient modulus of fabric will be studied in a later section.

3.4 Conclusions

The literature demonstrates that the design criterion of maximum vertical stress on the subgrade can be applied to the granular surface roads and the vertical strain in subgrade is a proven criterion for flexible pavement. Use of finite element and layered elastic theories predict the stresses which correspond to values measured in the field. Properties of granular materials and properties of soil subgrades are well characterized. Finite element or layered elastic analyses of roadways with fabric layers have not been performed; therefore, the criteria for design of roadways incorporating a fabric layer are not well developed. The uses of the finite element and layered elastic theories and criteria for design of roadways with fabric layers will be investigated in following chapters.

IV. PARAMETRIC STUDY OF ROADWAYS WITH A REINFORCED LAYER

The purpose of this section is to do a parametric study of the roadway structure with and without a reinforcing layer. The method of analysis used is the linear layered elastic theory.

4.1 Layered Elastic Theory

The layered elastic analysis is performed using the Chevron Computer Program (Chev 5L). This program is selected because it requires a minimum amount of computer time and it has been used successfully to predict stress and strain in roadway structures. The analysis is performed to study the effect of material properties on the radial stress in the bottom of the surface layer, the radial stress in the reinforced layer and the vertical strain and stress on the subgrade. These stresses and strain are selected because they could be used as failure criteria. The roadways considered are as follows: (a) roadway without reinforcing layer is a two-layer roadway (surface and subgrade); (b) roadway with reinforcing layer is a three-layer roadway (surface, reinforced layer and subgrade). The various parameters selected for the analysis are: (a) subgrade resilient modulus is assumed at 1500 psi (CBR of one) for all cases. Poisson's ratio is 0.45. (b) the resilient moduli for the surface layer are 1500, 3000, 7500, 15,000 and 30,000 psi and the Poisson's ratio is 0.3. For each value, the thicknesses of 5, 15, 25, 35 and 40 inches are analyzed. (c) the resilient moduli of the reinforcing layer are 15,000, 150,000 and 1,500,000 psi and Poisson's ratio is 0.3. Thickness is assumed to be 0.5 inch for all cases. (d) the load is a single 9000 pound load with a contact pressure of 70 psi. These parameters will provide a wide range of consideration. They cover the range of untreated granular materials or stabilized materials.

The subgrade may be considered stiff or soft on the basis of the modulus* ratio, since the stress obtained from linear layered elastic theory is dependent upon this ratio. Although the modulus of the subgrade has been selected as 1500 psi for the calculations, any modulus can be considered by using the proper modular ratio. However, the strain in the layer depends on the modulus of elasticity of the layer. The vertical strain in the subgrade can be calculated from the relation:

$$\varepsilon_z = \frac{1}{E} [\sigma_z - M(\sigma_r + \sigma_t)]$$

where: $\sigma_z, \sigma_r, \sigma_t$ = vertical stress, radial stress and tangential stress,

---

*The modulus of elasticity mentioned throughout the text refers to the resilient modulus.

μ = Poisson's ratio,

E = Modulus of elasticity of subgrade.

When the modular ratio is used, any materials could be considered. Typical values of modulus of elasticity of materials are the following: asphalt treated material 150,000-1,500,000 psi, cement treated soil 500,000-1,000,000 psi, lime-treated soil 50,000-200,000 psi, reinforced materials (fabric to steel plate) 1,000-16,000,000 psi, and soil subgrade 1,000-30,000 psi. A single wheel load of 9,000 pounds and a pressure of 70 psi were selected because they represent a common loading condition used by several investigators.

4.1.1 Results and Discussion

The results of the analysis are compared for roadways with and without reinforced layers using the ratio of modulus of elasticity explained earlier. Part of the data are shown in this text for the purpose of discussion. The rest is in the Appendix.

4.1.1.1 Radial Stress in the Bottom of the Surface Layer

Surface materials are either untreated or stabilized. First, untreated granular surface is considered. For an untreated granular surface the modulus of elasticity depends on the subgrade support conditions. The modular ratio is one to two for stiff subgrades and about five for soft subgrades as indicated by Heukelom and Klomp (20). Therefore, these modular ratios are considered. The limiting criteria for granular material could be radial tensile stress as shown by Gerrard, et al. (17). The tensile strength of unbound gravel and clay sand ranges from 5 to 25 psi. For unbound gravel with binder the tensile strength should be less than clay-sand; hence, 10 psi is selected.

Figure 4.1 shows the relationship between radial stress and thickness of the surface layer. In Figure 4.1(a) $E_{surface}/E_{subgrade} = 1.0$. The tension is very small for the two-layer system. When the reinforcing layer is inserted with moduli of 10, 100 and 1,000 times the subgrade modulus, the radial stress is reduced to compression in all cases. In case of $E_{surface}/E_{subgrade} = 2.0$ in Figure 4.1(b), the tensile stress for the two-layer system is less than 10 psi when the thickness of surface layer is greater than 12 inches. The radial stress decreases to less than 10 psi when the reinforcing layer is inserted in all cases. Figure 4.1(c) shows that the tensile stress is less than 10 psi when the thickness of the surface layer is 22 inches and over. When the modulus of the reinforcing layer is ten times the subgrade modulus, the radial stress in the surface layer decreases, but does not become compressive. Only when the modulus of the reinforcing layer used is 100 and 1,000 times the subgrade modulus

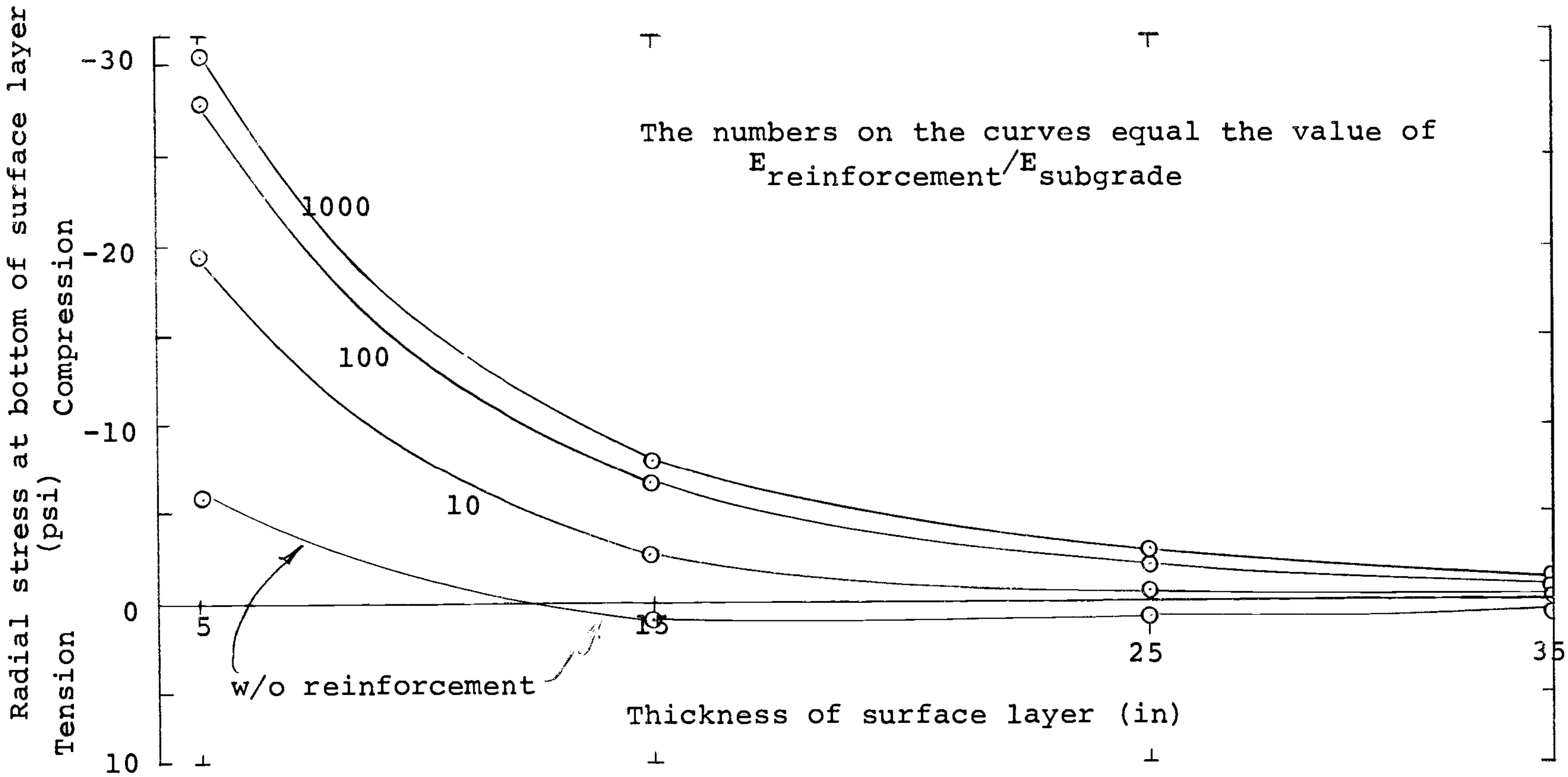


Figure 4.1(a). The relation between radial stress at the bottom of the surface layer and thickness of the layer with and without a reinforced layer for $E_{surface}/E_{subgrade} = 1.0$.

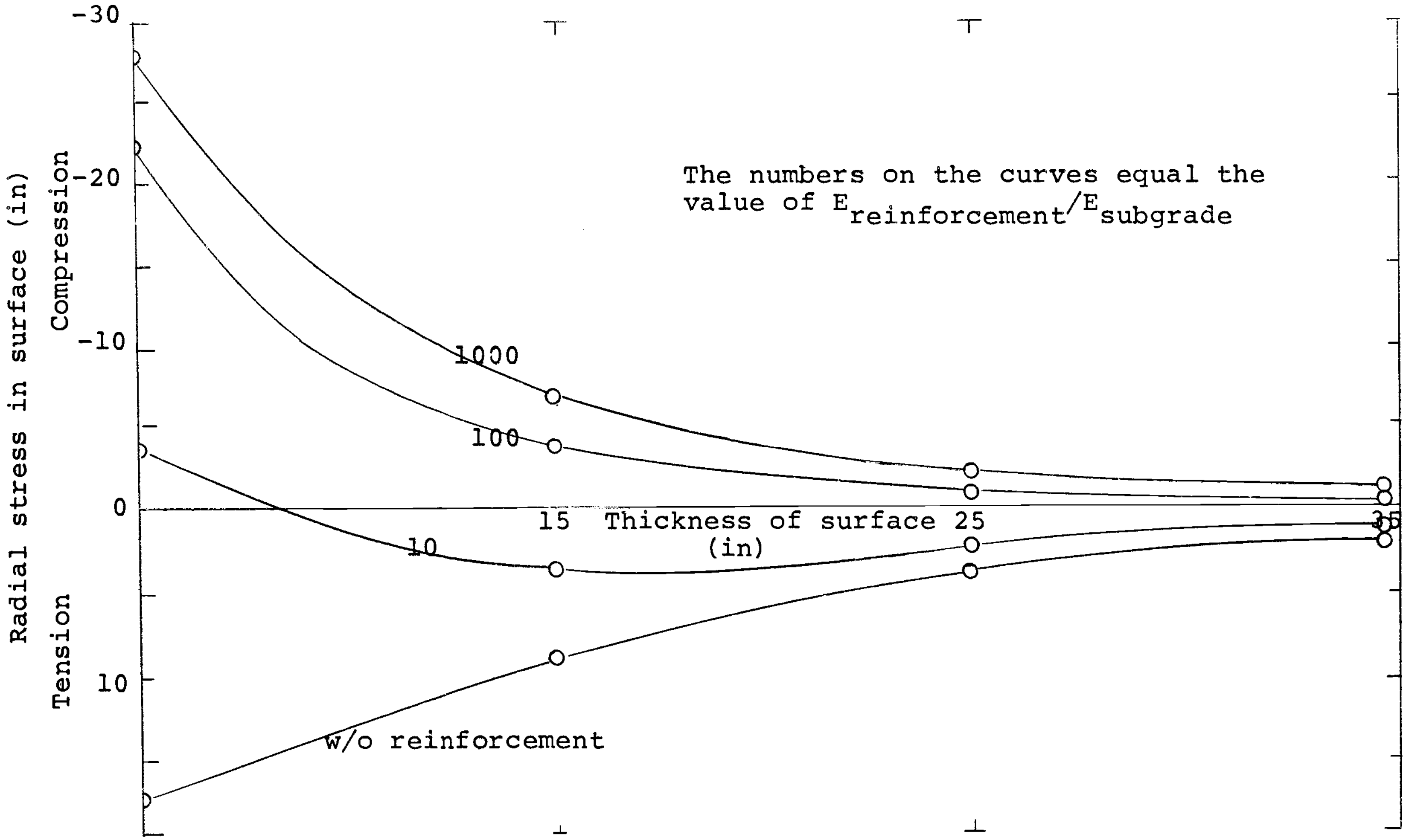


Figure 4.1(b). The relation between radial stress in surface and thickness of surface with and without reinforced layer for $E_{surf}/E_{subgrade} = 2.0$

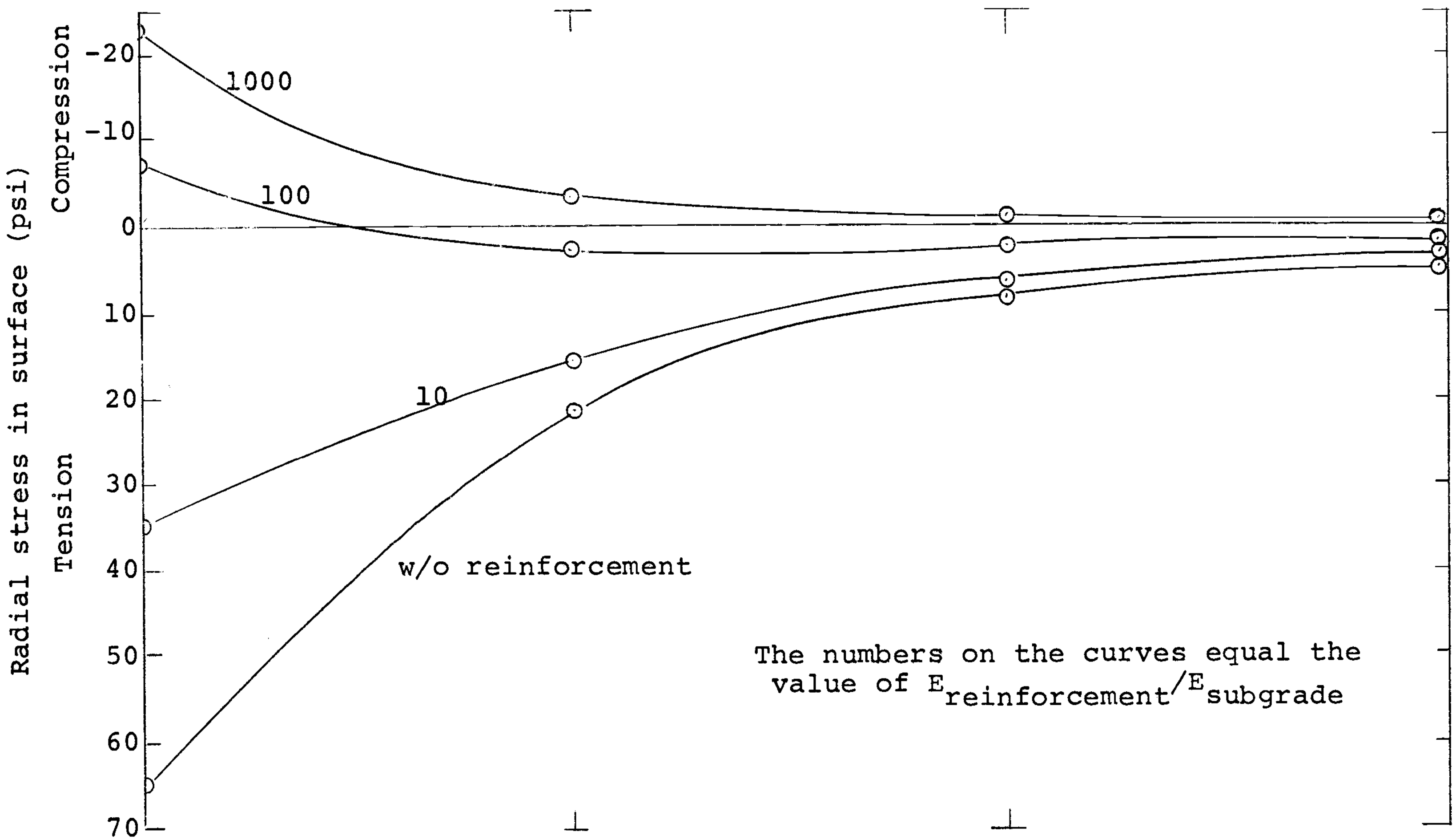


Figure 4.1(c). The relation between radial stress in surface and surface thickness with and without reinforced layer for $E_{surf}/E_{subgrade} = 5$

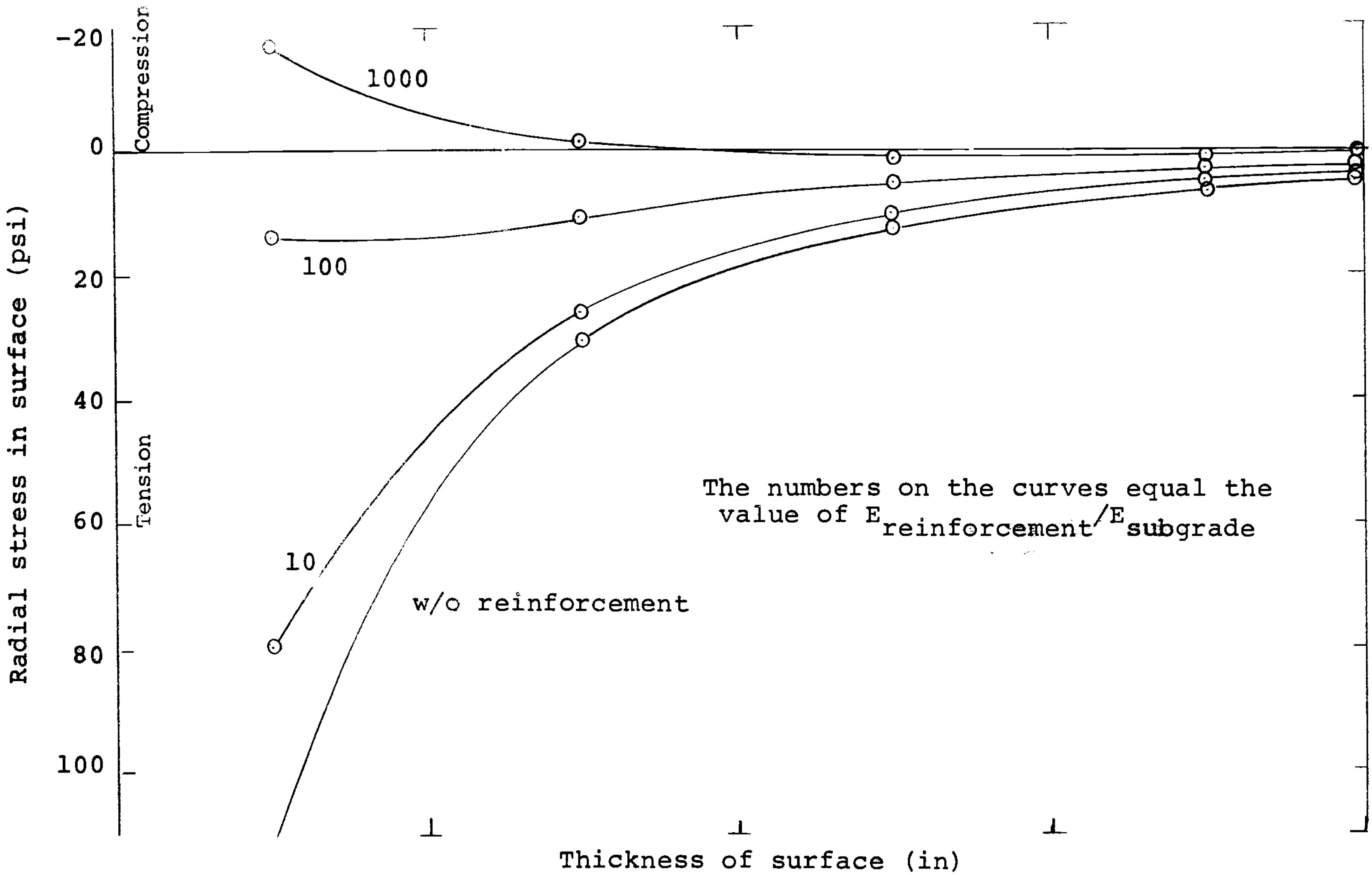


Figure 4.1(d). The relation between radial stress in surface and thickness of surface for $E_{surface}/E_{subgrade} = 10$

does the radial stress in the surface layer become compressive. Therefore, when the reinforcing layer is incorporated in granular surfaced roads it will decrease the radial stress and tend to reduce tensile failures in the bottom of the surface course.

It should be noted that in the computations the thickness of the reinforcement was always 0.5 inch. If the actual reinforcement being considered is different than this thickness, the modulus of the reinforcing material must be adjusted proportionally. When typical values of modulus (Figure 5.14) and thickness (Table 3.3) for the common fabrics are considered, it is apparent that the ratio of the modulus of the reinforcement to the modulus of the subgrade will be considerably less than ten, even for very soft subgrade.

These results suggest that the reinforcing effects of fabrics in gravel surfaced roads will be very small. Only for very, very soft subgrades might they be expected to have any benefit at all (for paved roads, they cannot be expected to have any significant effects). The calculations were performed using a 9000 lb wheel load. If the load is higher than 9000 lb, the stresses will also be higher, but the trends and the conclusions will not change.

4.1.1.2 Radial Stress in Reinforcing Layer

When stress is considered, the modular ratio may be used as a base of comparison since the stress depends on the modular ratio. The relationships between radial stress in the reinforcing layer and surface thickness are shown in Figure 4.2. Radial stress in the reinforcing layer is tensile in all cases. When the modulus of elasticity of the reinforcing layer is 1000 times the modulus of the subgrade, the radial stress ranges from 100 to 2,400 psi. When the modulus of elasticity of the reinforcing layer is 100 times the modulus of the subgrade the radial stress ranges from 50 to 450 psi. When the modulus of elasticity of the reinforcing layer is 10 times the subgrade modulus the radial stress ranges from less than 10 to about 100 psi. As the thickness is increased, the radial stress decreases. Considering that the fabrics have adjusted moduli of less than 1,000 psi, the ratio of $E_{reinforcement}/E_{subgrade}$ will be less than 10 even for very soft subgrades. Maximum radial stress in the reinforcing layer will be less than 500 psi. The fabrics have little chance to fail under a single wheel load of 9000 pounds with a pressure of 70 psi. The effects of loads larger than 9000 pounds will cause higher stress in fabric for the same conditions of roadway. Hence, an analysis of stress in fabric should be made before it is used. This will be discussed further in Chapter 7.

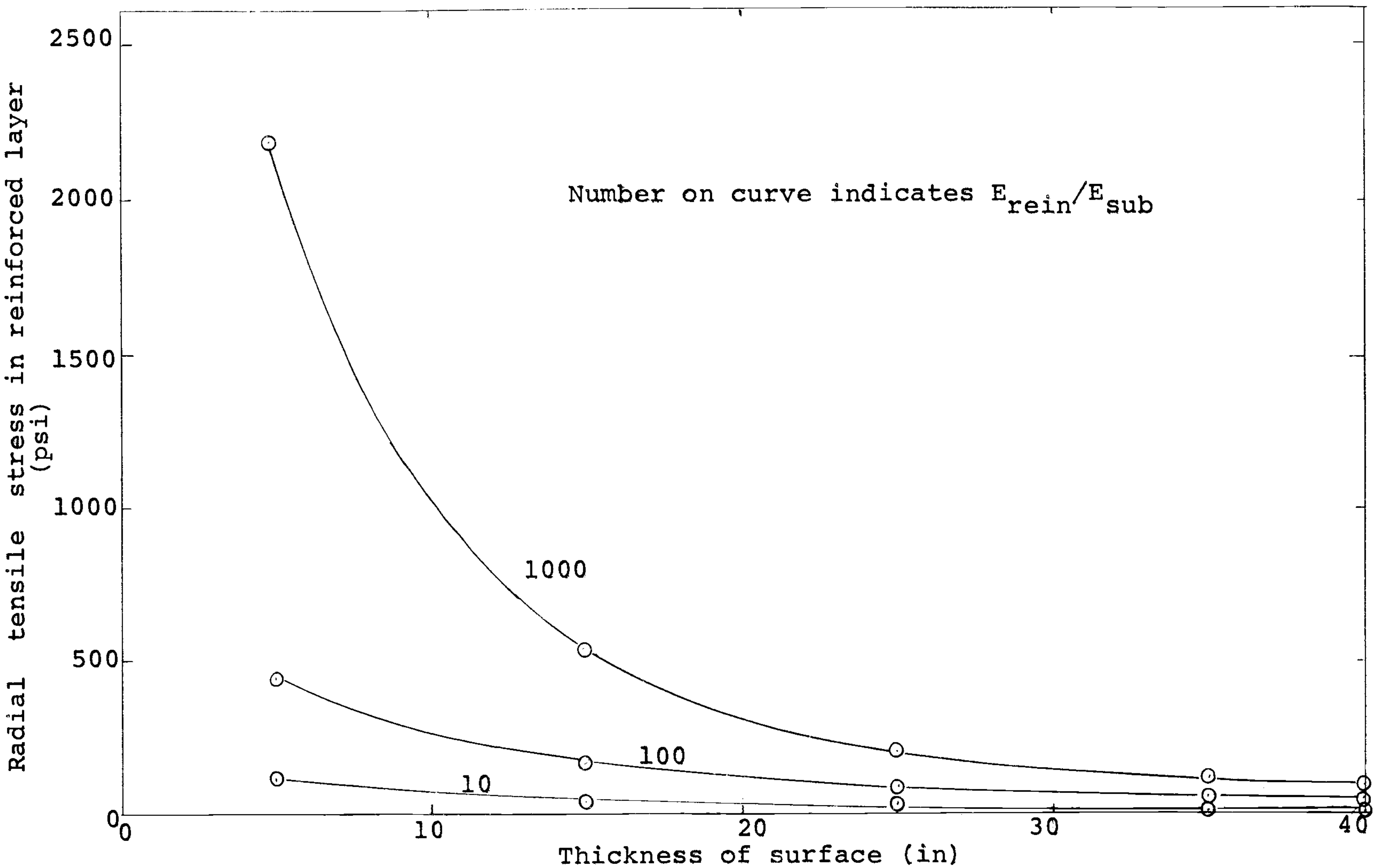


Figure 4.2(a). The relation between thickness of surface and radial (tensile) stress in reinforced layer for $E_{surface}/E_{subgrade} = 2$.

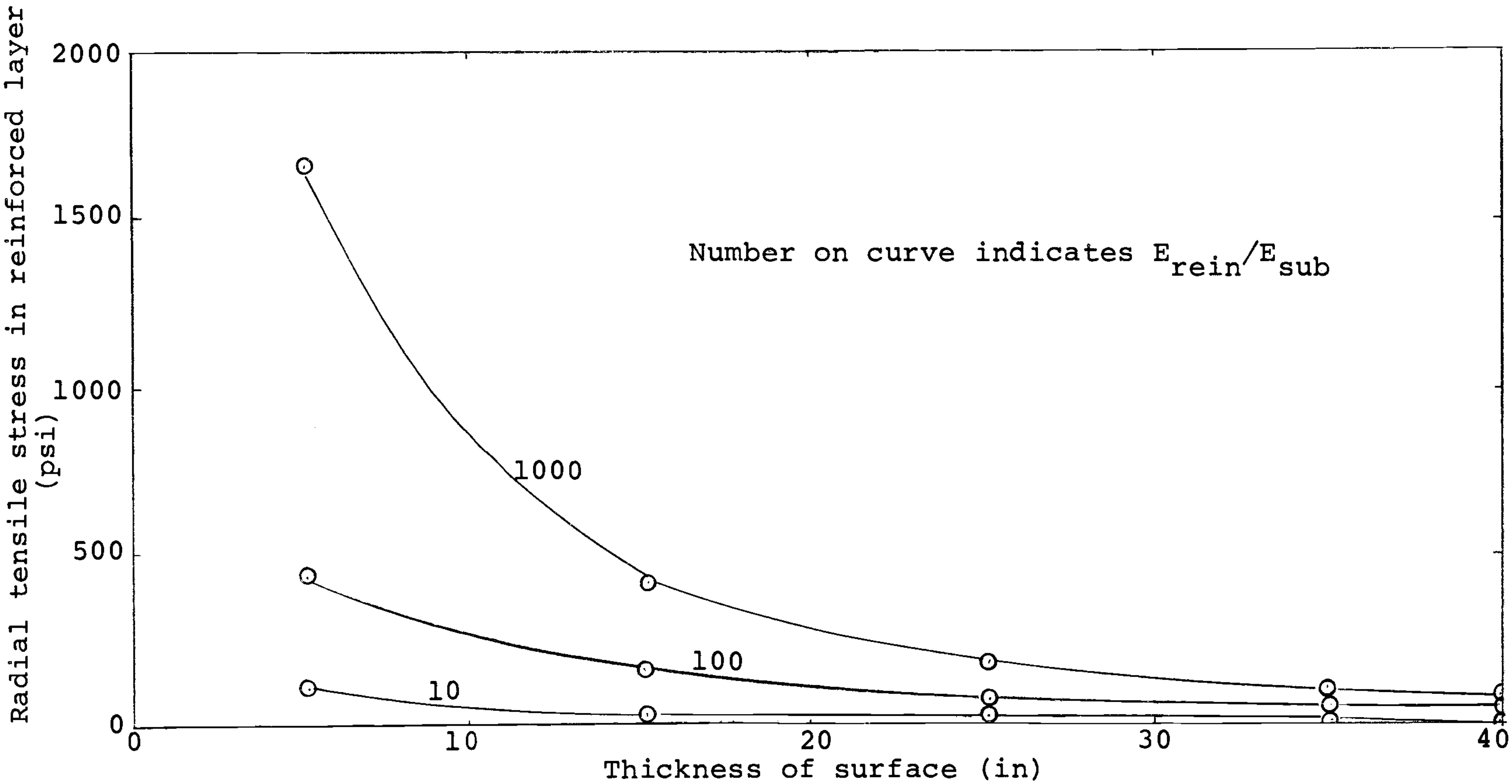


Figure 4.2(b). The relation between thickness of surface and radial (tensile) stress in reinforced layer for $E_{surface}/E_{subgrade} = 5$.

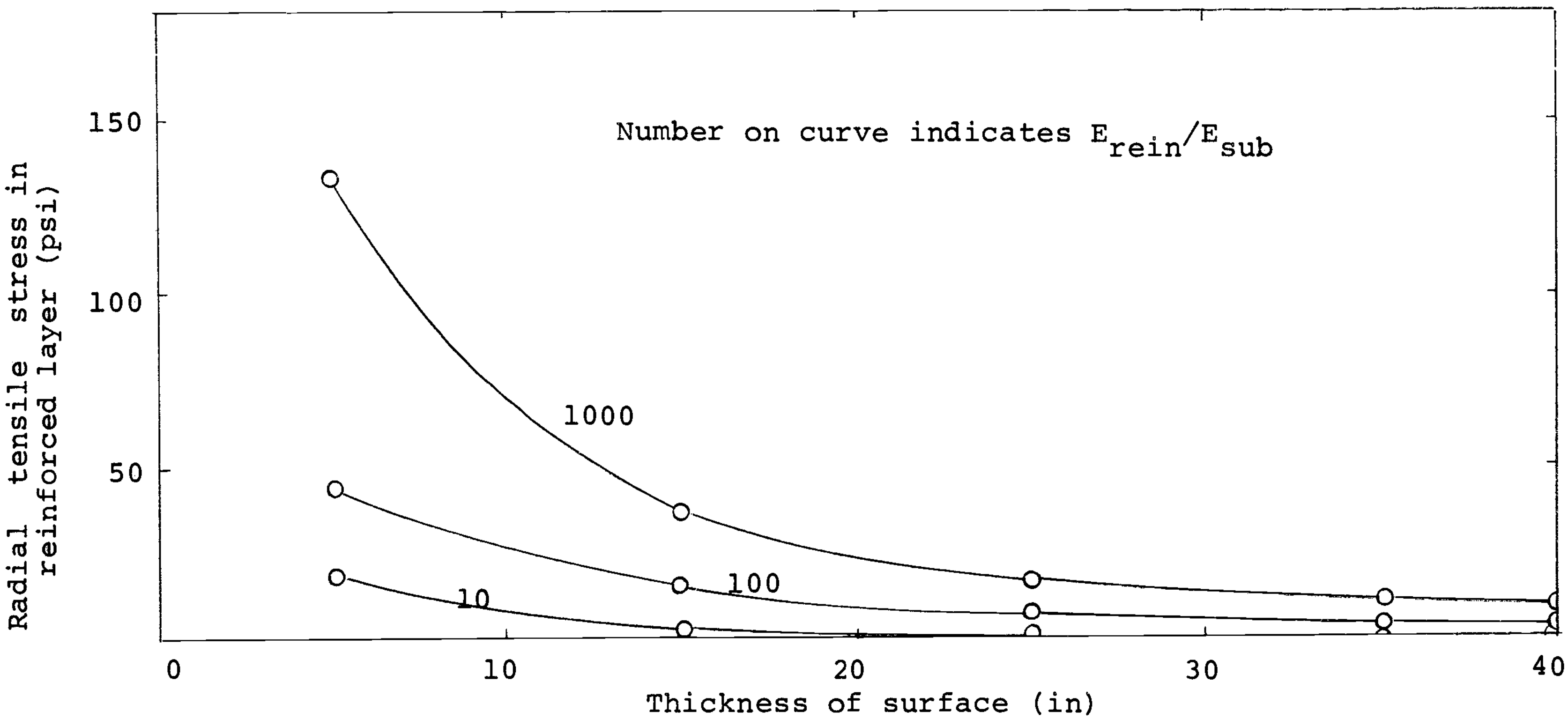


Figure 4.2(c). The relation between thickness of surface and radial (tensile) stress in reinforced layer for $E_{surface}/E_{subgrade} = 10$.

4.1.1.3 Vertical Stress on the Subgrade

The relationships between thickness of surface and vertical stress on the subgrade are shown in Figure A.1. From this figure, the difference between the thickness of the surface layer with a reinforcing layer at the same stress is computed and defined as a thickness reduction. Then the relationship between thickness reduction and maximum vertical stress on the subgrade is plotted in Figure 4.3. From this relation in all cases the thickness reduction is between 0.5 and 5 inches. If the soft subgrade has a modulus of 500 psi and the fabric has an adjusted modulus of 1,000 psi, the ratio of $E_{reinforcement}/E_{subgrade}$ is 2. When a granular surface is used, the $E_{surface}/E_{subgrade}$ is from two to five and the thickness reduction is less than one inch. When a stabilized surface is used the $E_{surface}/E_{subgrade}$ is more than ten and the thickness reduction approaches zero.

4.1.1.4 Vertical Strain on the Subgrade

The relationship between maximum vertical strain on subgrade and thickness for several values of $E_{surface}/E_{subgrade}$ is shown in Appendix Figure A.2. The thickness reductions obtained from these relations are plotted in Figure 4.4. The subgrade considered is 1500 psi. For the case of a granular surface which is shown in Figure 4.4(a) ($E_{surface}/E_{subgrade} = 2.0$ to 5.0), it is found that when

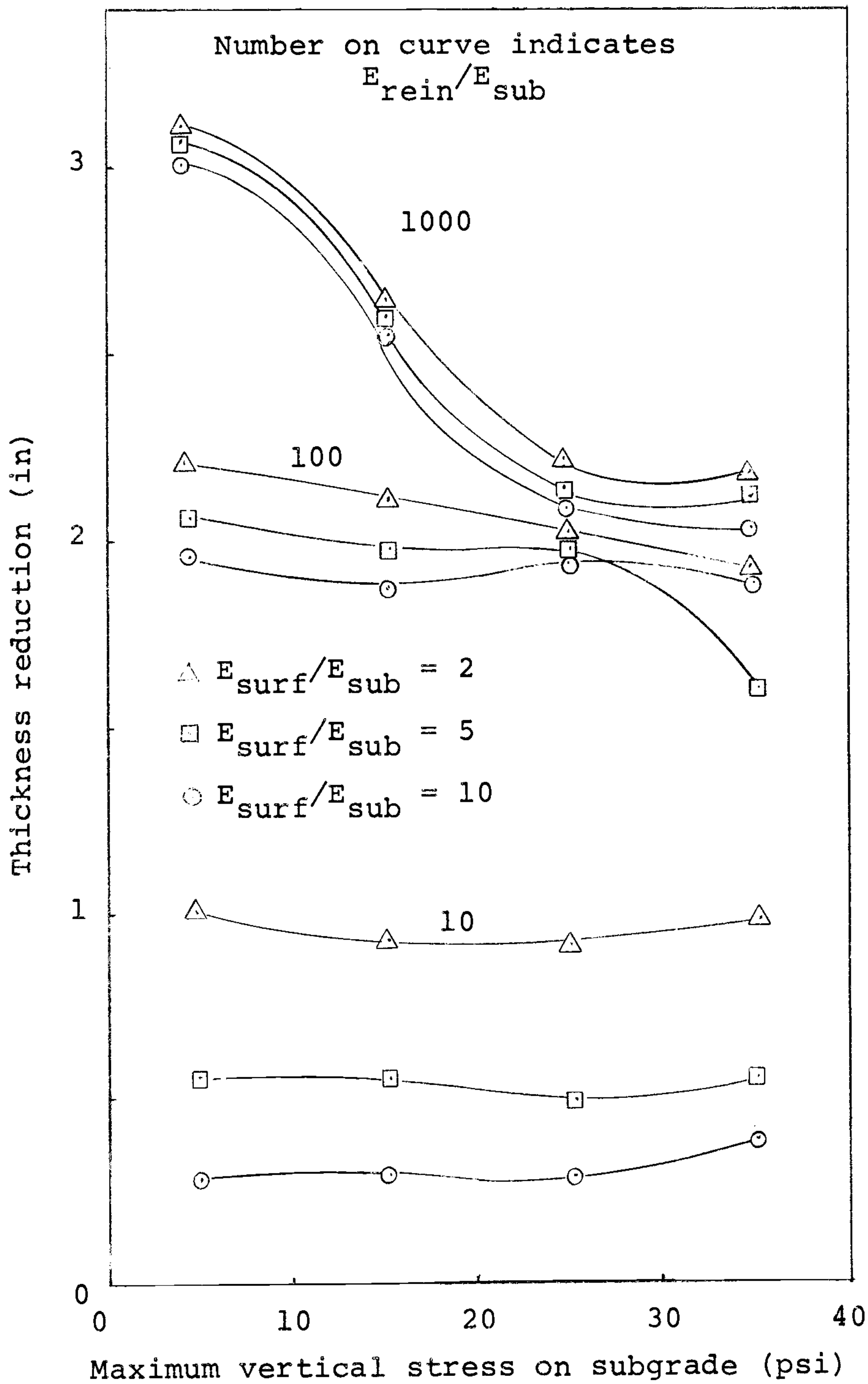


Figure 4.3 The relation between thickness reduction and vertical stress on subgrade.

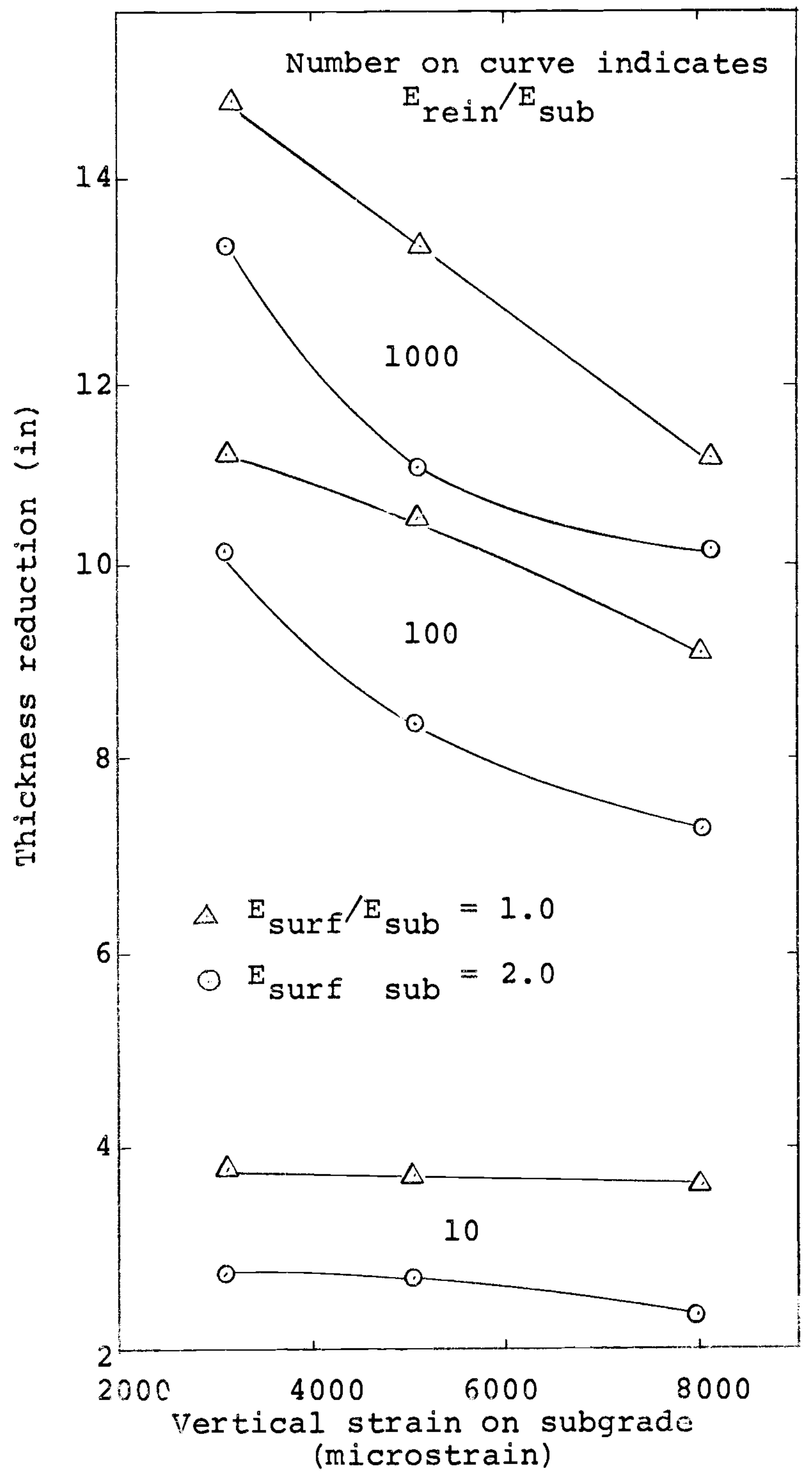


Figure 4.4(a). The relation between thickness reduction and vertical strain on subgrade.

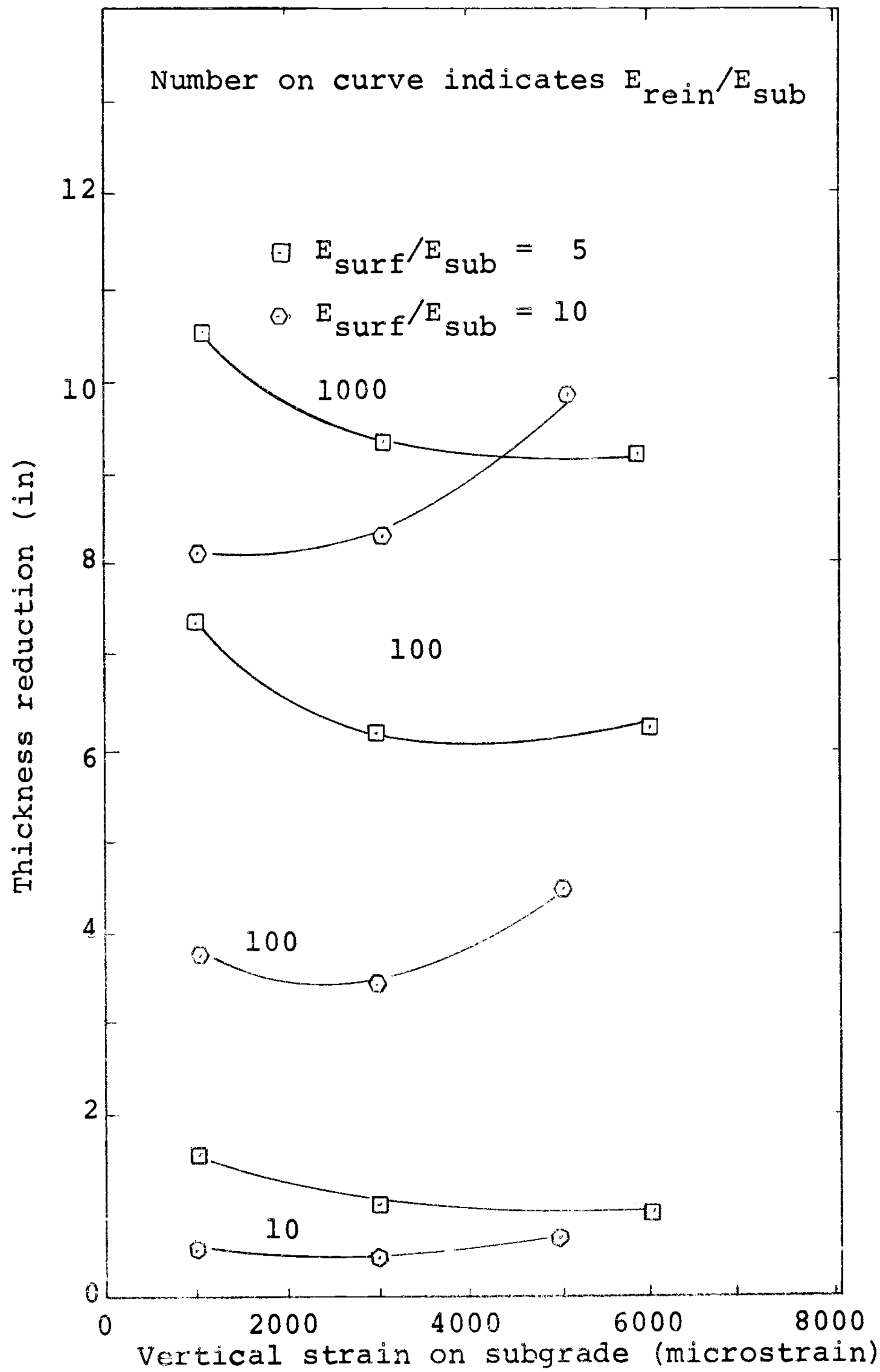


Figure 4.4(b). The relation between thickness reduction and vertical strain on subgrade.

$E_{reinforcing}/E_{subgrade}$ is ten, the thickness reduction is about three to four inches depending on limiting vertical strains.

In the case of a stabilized surface ($E_{surface}/E_{subgrade}$ is greater than five) the thickness reduction is low. This is shown in Figure 4.4(b). Therefore, the fabric is not likely to provide significant reinforcement for paved roads. If it has any application it will only be for gravel surfaced roads.

When the ratio of $E_{reinforcing}$ to $E_{subgrade}$ is in the range of 100 to 1,000, the thickness reduction is from 12 to 17 inches. These moduli, however, are much higher than possible with the commonly used fabrics.

It should be noted that when maximum vertical stress on subgrade criteria in Figure 4.3 is compared to the maximum vertical strain criteria in Figure 4.4, the thickness reduction obtained from strain criteria is about three times higher than stress criteria in all cases.

4.2 Conclusions

When a low modulus fabric is inserted below a granular surface, the radial tensile stress is significantly less than for a roadway structure without fabric.

The radial tensile stress in the fabric due to 9,000 pound wheel loads is less than one-half of the tensile strength of the common fabrics on the market.

When maximum vertical stress criteria in the subgrade is used as a base for comparison little thickness reduction is noticed when fabric is inserted; however, when comparison is based upon maximum vertical strain criteria in subgrade, thickness reduction is normally three to four times larger.

When a high modulus surface is used (e.g. stabilized surface) essentially no thickness reduction is expected when the fabric is used.

V. PROGRAM OF MODEL TESTS

The purpose of this chapter is to present the overall test scheme. This includes descriptions and discussions of the test equipment, the design of the program of loading, the preparation of materials and data collections of the model tests of the roadway structure, and the evaluation of material properties used in the tests.

5.1 Loading Programs

As discussed previously, several problems concerning the performance and design of roadway structures incorporating a fabric reinforcing layer are still unsolved. The comparison of the behavior of roadways with and without fabric is needed to determine the conditions for which fabric will significantly improve the distribution of load. The effects of the magnitude of load, type of fabric, size of wheel, thickness of base and number of load applications on the behavior of fabric are not clear. A sound theory that can be used to analyze the system, and well developed criteria for design of roadway structure with a fabric layer are needed. For these reasons, a loading program will be planned to accomplish these goals.

The model tests were designed to use a repeated load to simulate the traffic load. Typical test sections consisted of a granular surface, fabric and a soil subgrade.

The test conditions are presented in Table 5.1. The fabric used in the test was primarily Fibretex 400. The model tests were designed to investigate several subgrade support conditions. Test 1 was on a subgrade stiffer than CBR of 1. Test 6 was on softer subgrades with CBR less than 1. These test conditions were to indicate the effectiveness of fabric as a reinforcement. Tests 2, 4 and 5 were without fabric. The thickness of base was also varied in these tests. The effect of different pressures was studied in Test 3. In Test 4, a filter layer was used to determine if the filter layer would assist in decreasing rutting as well as the fabric. Mirafi fabric was used in Tests 7. Only one subgrade was used.

5.2 Description of Test Equipment

The roadway structure test model was constructed over a soil subgrade in a circular tank five feet in diameter and four feet deep, shown in Figure 5.1. The tank was corrugated steel. The bottom of the tank was steel plate. The load system was mounted on a beam above the tank.

The loading system is diagrammatically shown in Figure 5.2. It is designed to produce a repeated load of a single pulse of variable magnitude and duration. The maximum load is approximately 9000 pounds. The duration of the load is 1.5 seconds. The load is repeated five times per minute. The system operates on compressed air. The pressure

Table 5.1 Test sections.

	Test I			Test	Test III			Test	Test	Test VI			Test VII	
	A	B	C	II	A	B	C	IV	V	A	B	C	A	B
Gravel thickness (in.)	20	15	10	15	10	10	10	15	15*	20	15	10	15	10
Subgrade	CBR > 1			CBR > 1	CBR < 1			CBR < 1		CBR < 1			CBR < 1	
Fabric	Fibretex 400			none	Fibretex 400			none	none	Fibretex 400			Mirafi 140	
Load (10^3lb.)	9	9	9	9	9	5	3	9	9	9	9	9	9	9
Pressure (psi)	70	70	70	70	70	40	23	70	70	70	70	70	70	70

*Includes four inch sand filter layer.

Figure 5.1. Model of roadway structure in circular tank.

regulator controls the air pressure into the system. The solenoid valve controls the air intake and exhaust of the actuator. The cycle and duration of the load are set by the timer. The force from the actuator is applied to the roadway structure model through the rigid plate of diameter 12.8 inches. When a 9000 pound load is used with this plate, the pressure on the roadway structure is 70 psi. The load is controlled by the air pressure in the system and the height of the airstroke of the actuator.

To compare the effect of load on the system in the tank to the effect of the wheel load on the real roadway structure, the major effects are considered in the following three sections.

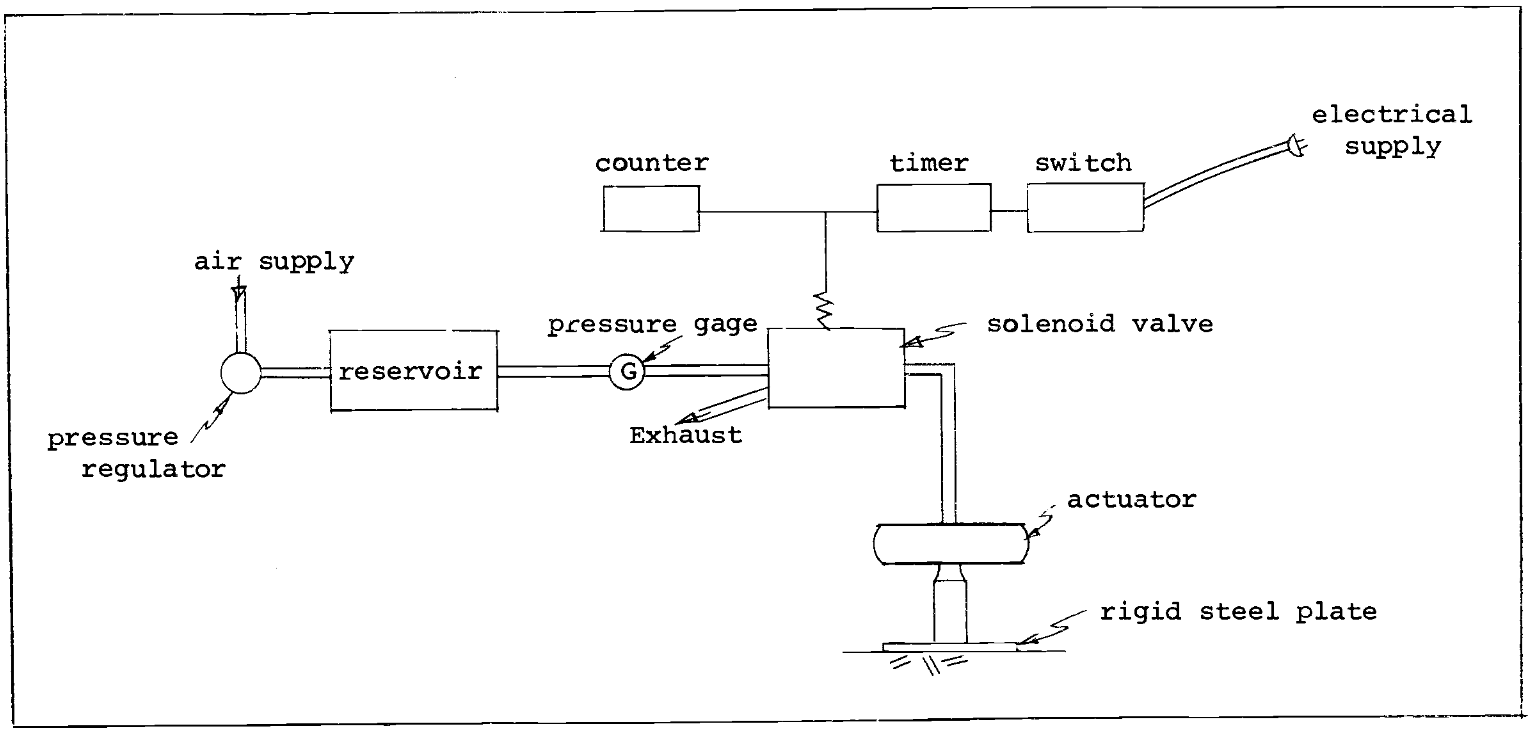


Figure 5.2. Diagramatic sketch of loading system.

5.2.1 The Effect of Rigid Load Plate

In the model test, the load is applied through a rigid plate, but on a real roadway the wheel load resembles a flexible plate. The only data collected are the permanent and elastic deflection. Therefore, the effect of a rigid plate on deflection will be considered. The relationships which were solved by Burmister (11) for two-layer pavements are the following:

$$\Delta_{fx} = 1.5 \frac{Pa}{E_2} F_2$$

$$\Delta_{RD} = 1.18 \frac{Pa}{E_2} F_2$$

Therefore, the relationship between a rigid plate and a flexible plate is $\Delta_{RD} = 0.79\ \Delta_{fx}$, indicating that the maximum deflection of a rigid plate is about 20 percent less than that of a flexible plate.

Hicks and Monismith (26) used layered elastic theory to analyze flexible pavements and compared deflections from the theory to those measured in the field. It was found that after the value of deflection from the layered elastic analysis was reduced about 20 percent, the actual deflection slightly overestimated. This confirmed that the rigid plate deflection is about 20 percent less than flexible plate deflection.

5.2.2 Effect of Tank Boundary

The test tank confines the experiment within limited boundaries, but the roadway structure in the field has more extended boundaries. The effect of this boundary inconsistency will be solved using the SAP IV finite element program (5). The details of the analysis are in Appendix B. The analysis shows that the tank boundary reduces the surface elastic deflection about 30 percent.

5.2.3 Effect of Load Duration

The load duration also has a significant effect on strains. Times of loading for the laboratory tests recommended by several researchers (34) are in Table 5.2. Barksdale (6) recommended times of loading as shown in Figure 5.3. This figure shows that for slow traffic typical of granular surface roads the vertical stress pulse will be 0.05 to 0.1 second. Sparow and Tory (42) studied the effect of load duration on the stress and strain from a model test. The durations of their study varied between 0.03 to 1.5 seconds but, the stress measured for different durations was found to be constant. The vertical strain, however, decreased by 10 to 20 percent.

Figure 5.4 shows the typical load and duration used in this study. The magnitude is 9000 pounds and the duration is about two seconds, which is the minimum duration possible with the loading system at this load. The duration

Table 5.2. Summary of recommended loading times for testing of asphalt concrete stiffness (Monismith *et al.* [35]).

Type of Pavement	Investigator(s)	Vehicle Speed	Loading Time or Frequency
Highway	Finn *et al.* (3)	30-40 mph	0.015 sec
	Hofstra and Valkering (4)	—	0.4 x d where d = length of strain signal
	Miura (5)	25-50 mph	0.04 to 1.0 sec
	Thrower *et al.* (6)		length of stress pulse at top of subgrade*
Airfields	Witczak (7)	10-20 mph	2 Hz

*For very soft asphalt layers, use the length of the pulse in the asphalt layer.

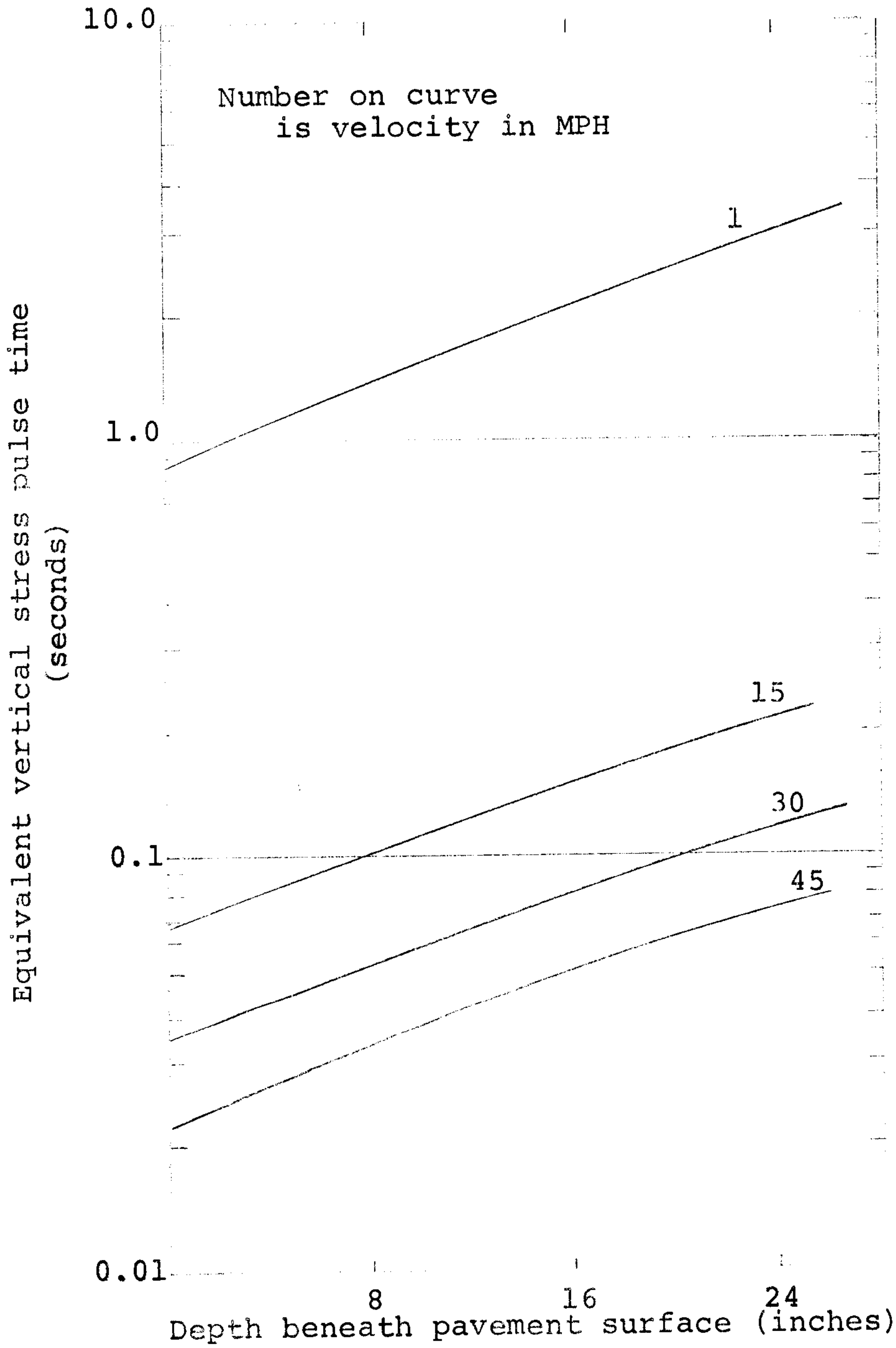


Figure 5.3. Variation of equivalent vertical stress pulse time with velocity and depth (Barksdale (6)).

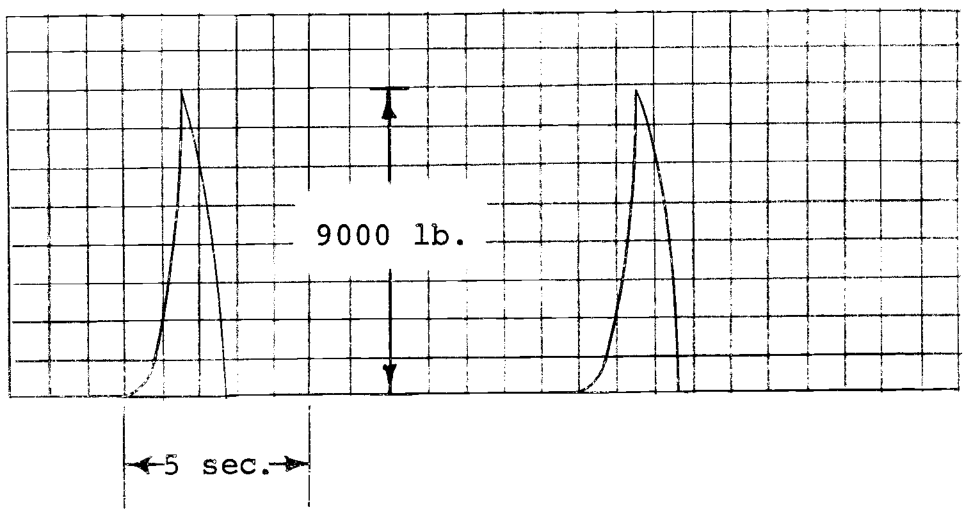


Figure 5.4. Typical load in test sections.

is also the same for the 3000 pound and 5000 pound loads. This duration is about 20 times the duration recommended by Barksdale (6). Therefore, the strains obtained from the tests will tend to be about 10 to 20 percent higher than would be expected from actual traffic loads.

There are still several effects which make repeated steel plates different from real traffic, including vibration and traction forces; however, these effects are excluded from the theoretical analysis. Considering the three main effects from the above discussion, the tank boundary and rigid plate tend to lower the deflection while the longer load duration will tend to increase the deflection. Therefore, these effects tend to balance out; however, it appears the net effect will be to reduce elastic deflection by approximately 30 percent.

5.3 Preparation of Materials in the Tests

The subgrade is prepared to approximately the desired support condition by controlling the moisture content. The subgrade is compacted using a hand tamper of three inches by three inches with a weight of about twelve pounds. The fabric layer is laid on the prepared subgrade. Then the granular materials are placed on the top and compacted with the hand tamper in eight-inch lifts with about four blows per lift.

5.4 Data Collection and Interpretation

The materials properties data collected in each test are density by sand cone (ASTM-D1556) of subgrade soil and granular surface, the moisture contents of the soils, the cone (31) and Proctor penetrometer readings for the subgrade.

The data interpretation will be based on the comparison of rut depth, number of repetitions to cause the rut depth and subgrade strength of test sections. In addition, the elastic deflection is to be compared to the theoretical analysis. Therefore, the elastic and permanent deformation of the surface, fabric, and top of the subgrade are measured. After the test is completed, the condition of fabric and profile of the test sections will be observed. The instrumentation of the test is shown in Figure 5.5. The

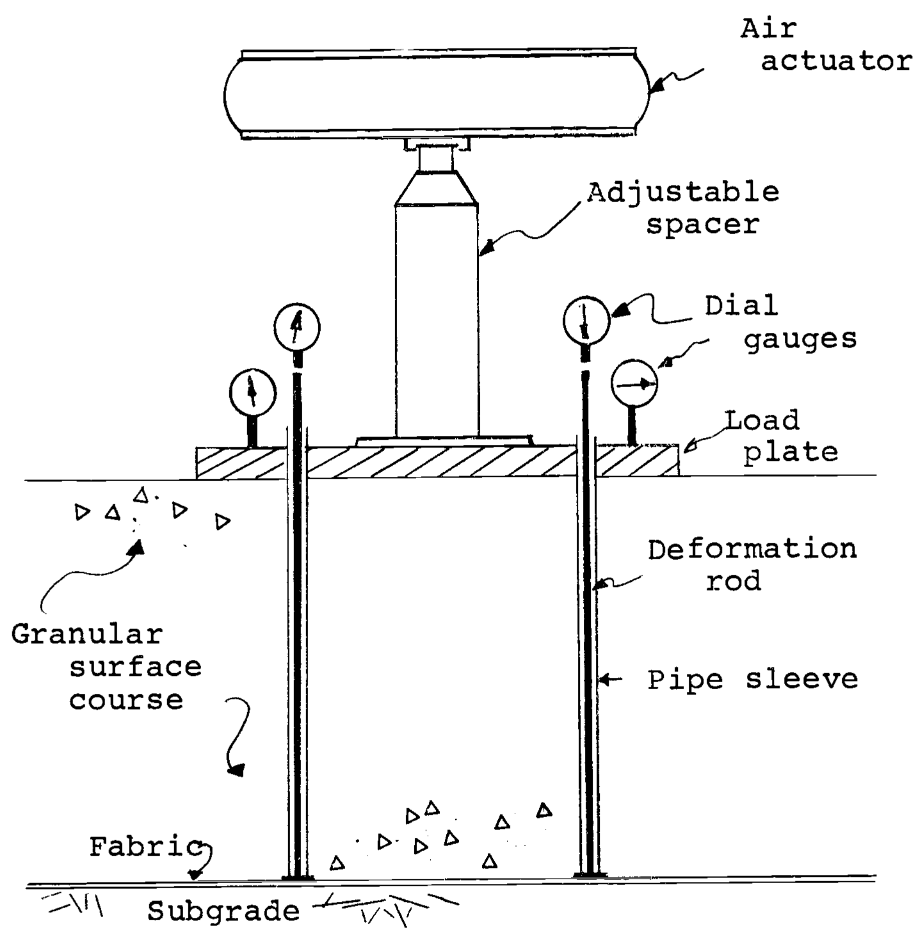


Figure 5.5 Instrumentation.

dial gages will be placed on each side of the steel plate so that the average value can be obtained.

5.5 Properties of Materials

Various properties of the materials used in the test will be presented here. The tests involve both static and dynamic properties of the materials. The dynamic tests are performed to simulate effects of a repetitive wheel load on the roadway structure.

5.5.1 Properties of Subgrade Soil

The soil subgrade is fine grain soil, classified as ML-CL by the Unified Classification System and A-6 by the AASTHO System. Some properties are shown in Table 5.3 Grain size distribution is shown in Figure 5.6. The support condition of the subgrade soil can be altered by varying the moisture content.

Table 5.3. Properties of subgrade soil.

Plastic limit(%)	Liquid limit(%)	Plasticity index (%)	Standard AASTHO Maximum dry density (lb/ft^3)	Standard AASTHO Optimum moisture content(%)
21.7	33.6	11.9	99.8	20

5.5.1.1 Static Strength Tests of Subgrade soil

The static methods used for evaluation of the subgrade material are cone penetrometer, Proctor penetrometer, California Bearing Ratio and vane shear tests. In the evaluation of subgrade materials in the model test, the cone penetrometer and Proctor penetrometer are used because they are very simple and fast and can be correlated to CBR and shear strength. The CBR and shear strength from vane shear are also used to evaluate the properties of soil. These strength indices are widely used by engineers. The CBR and shear strength can be found by the relations of CBR and

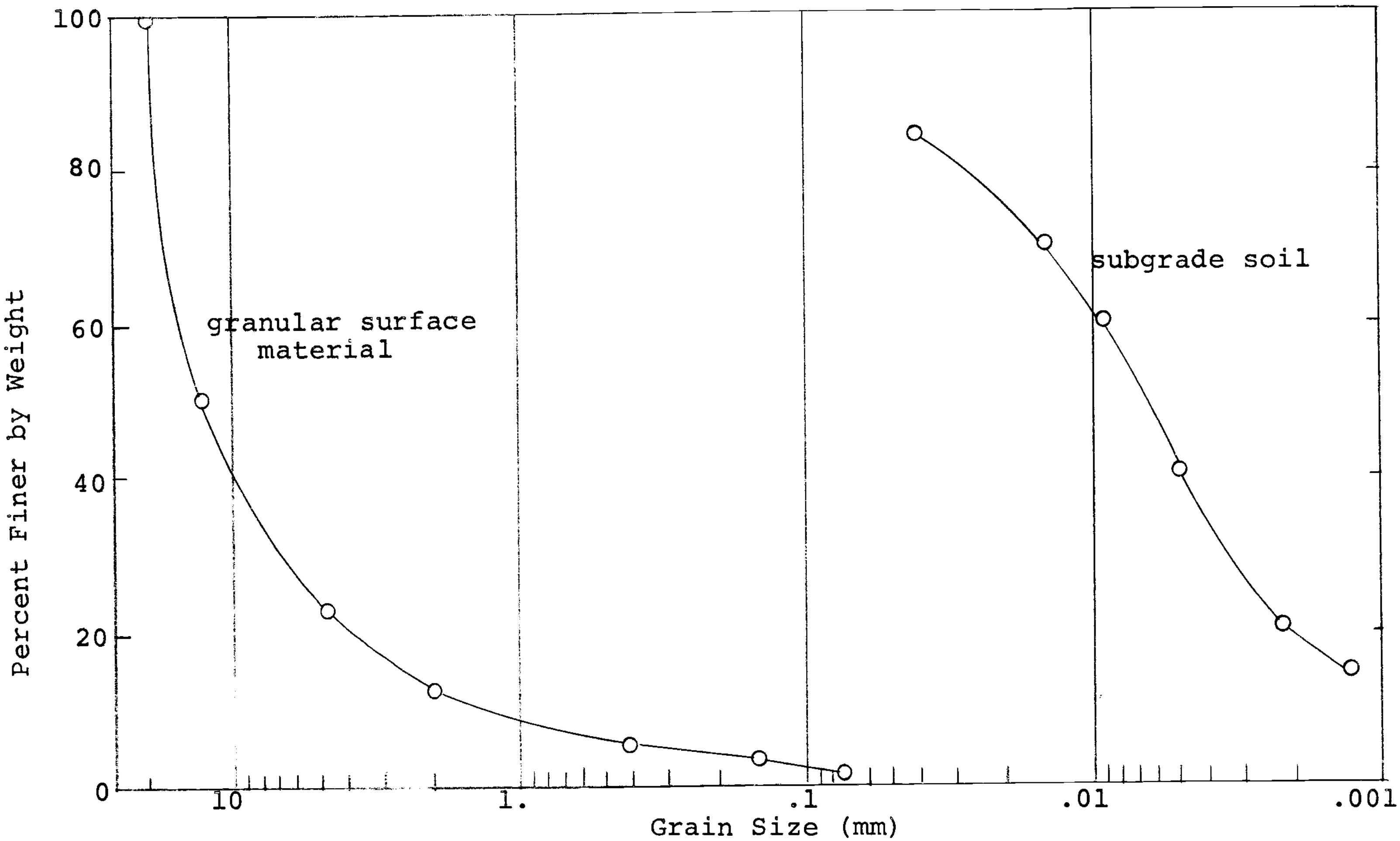


Figure 5.6. Grain size distributions of soils.

shear strength to soil penetrometer and cone penetrometer developed for the subgrade soil.

The Corps of Engineers (31) developed the cone penetrometer for trafficability studies. The penetrometer consists of a 30 degree cone with a one-half square inch base area mounted on the end of a shaft. The force per unit area obtained from the cone penetrometer is called cone index. The cone index is the force required to push the cone into the soil divided by the area of cone base. Truesdale and Selig (43) used a standard Corps of Engineer cone with a hydraulic supporting system for a rapid test of compacted soil. The support system provided a constant rate of testing. They indicated that the cone penetrometer has several advantages over the CBR test. It requires no surface preparation, is extremely rapid, and permits an examination of vertical variation in the lift. The cone penetrometer test followed the method recommended by the Corps of Engineers (31).

The Proctor penetrometer is similar to the cone penetrometer, except that it incorporates a circular flat plate instead of a cone. Flat plates can be selected with circular areas of 1, 3/4, 1/2, 1/3, 1/5, 1/10 and 1/20 square inch. The procedure used in the tests follows ASTM-DI558.

The California Bearing Ratio test procedure follows AASTHO-T-193. The CBR was selected because it is a very widely used strength index in roadway design. Also, it can be used to estimate the dynamic modulus from the correlation Es = 1500 CBR.

5.5.1.2 Results and Discussion of Laboratory Strength Tests on Subgrade Soil

The cone index, penetration resistance, CBR and shear strength are plotted against moisture content in Figure 5.7. All the strength indices decrease as the moisture increases. Since the strength is dependent on moisture content, in preparation of the subgrade soil the strength of the soil is controlled with the moisture content. The required water contents were approximated from the relations in Figure 5.7.

The relationships between penetration resistance and cone index and CBR are shown in Figure 5.8 and Figure 5.9, respectively. These relations enable finding the CBR from the soil penetration resistance and cone index. The relationship between cone index and shearing resistance is shown in Figure 5.10. The relationships of cone index to CBR and cone index to shearing resistance developed for the soil used in this study are slightly different from the relationships reported by Barenberg, et al. (4).

5.5.1.3 Dynamic Modulus of Subgrade Soil

Two samples were prepared to the density and moisture of the soil in the model test for dynamic modulus testing. Triaxial repeated load tests were performed on samples eight inches high and four inches in diameter. The duration

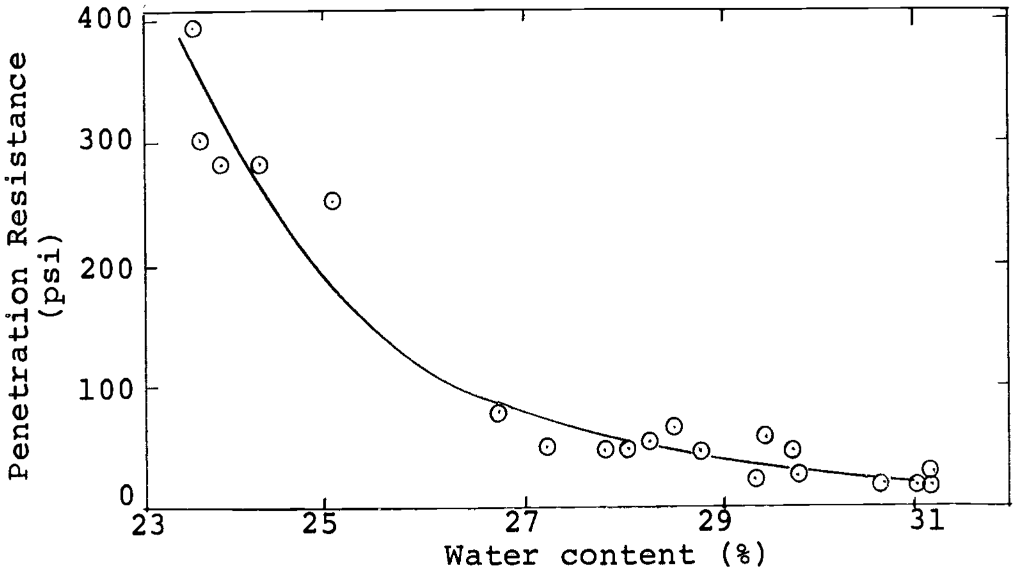


Figure 5.7(a). Penetration resistance versus water content.

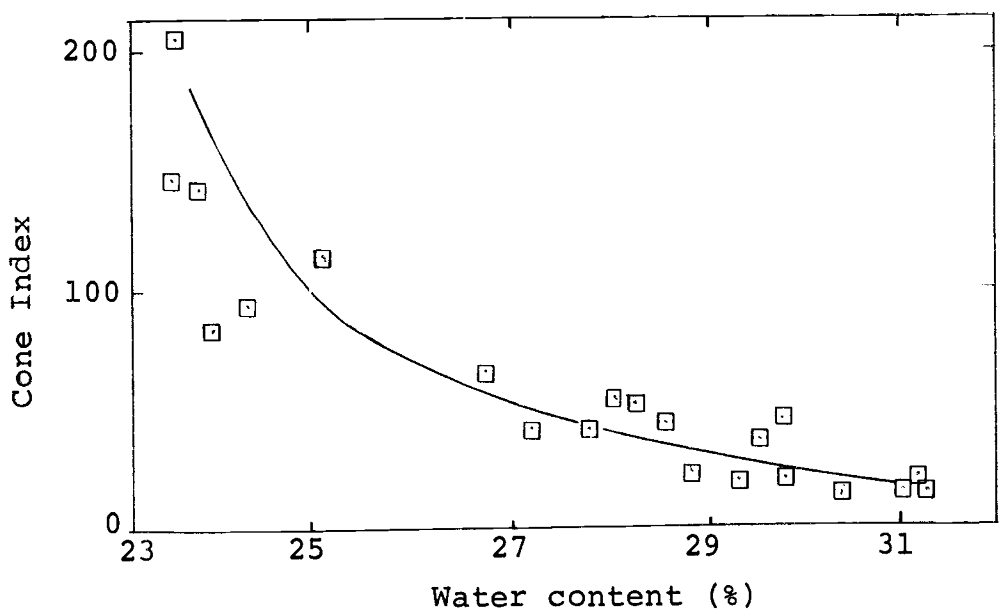


Figure 5.7(b). Cone index versus water content.

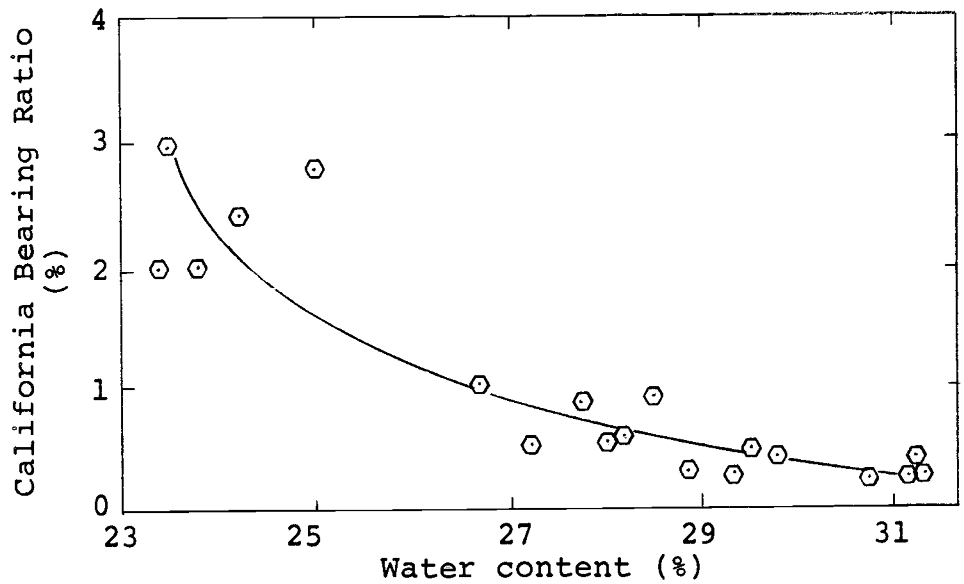


Figure 5.7(c). California bearing ratio versus water content.

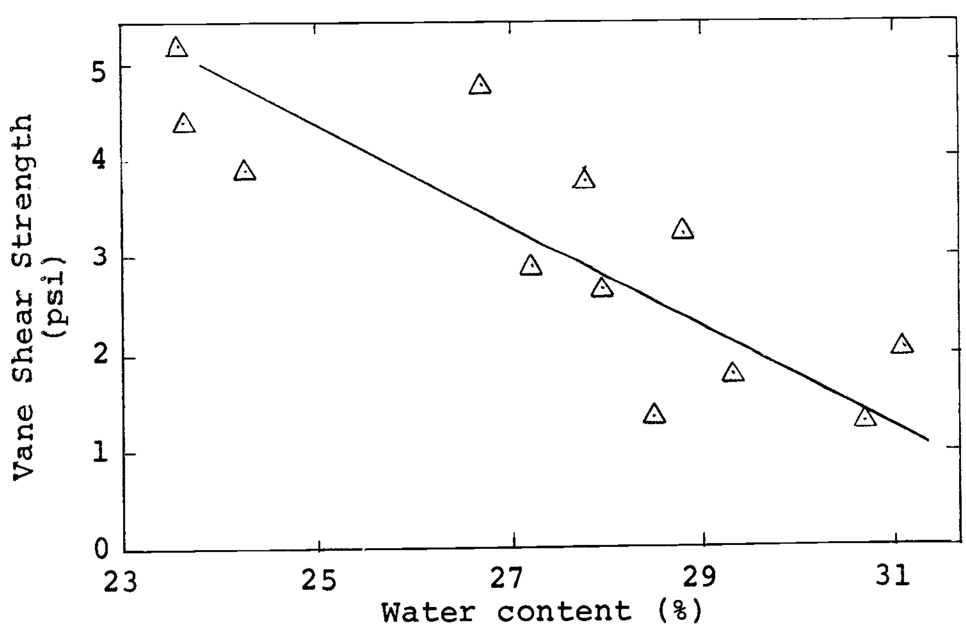


Figure 5.7(d). Vane shear strength versus water content.

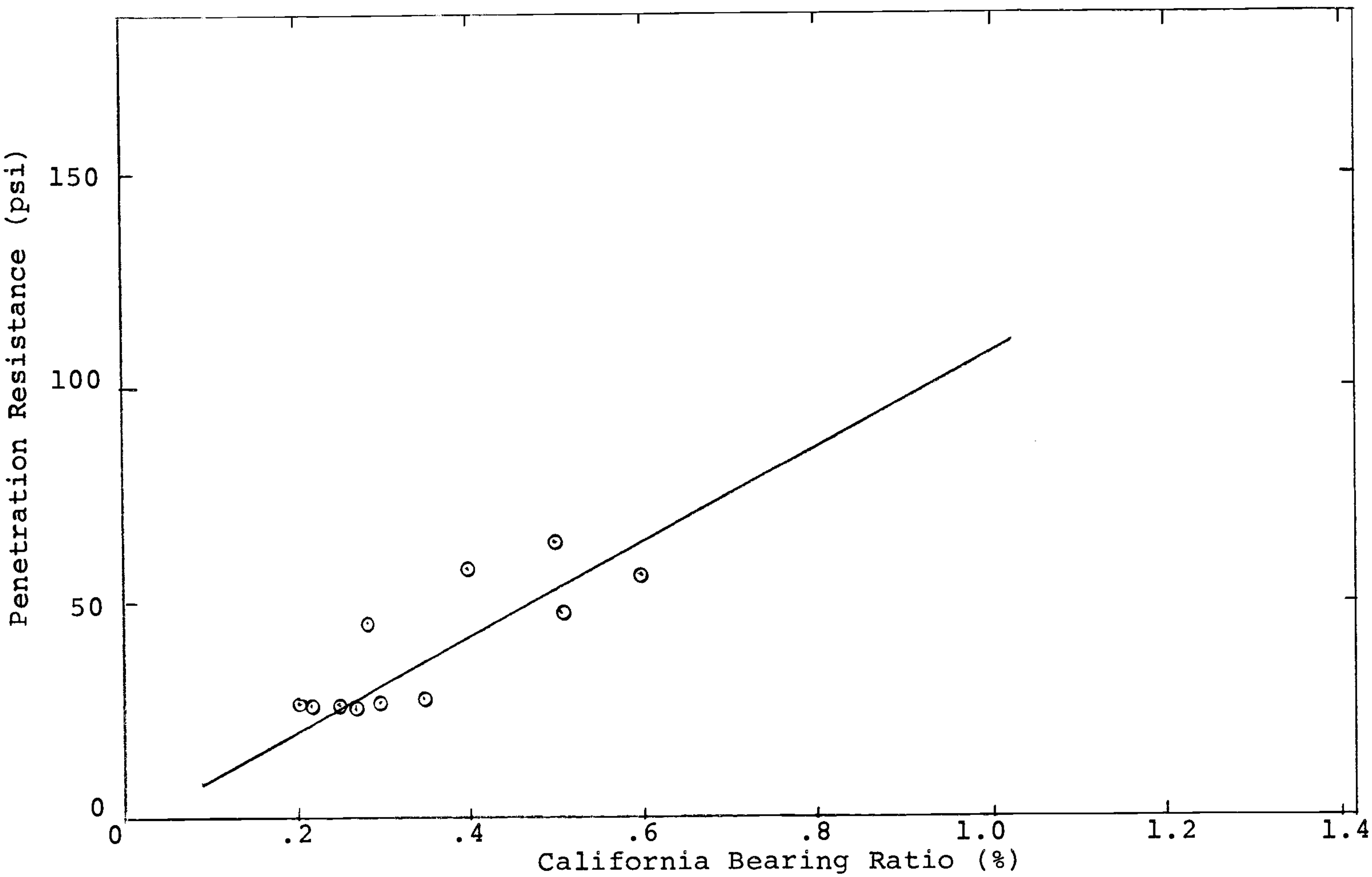


Figure 5.8. Relation between penetration resistance and California Bearing Ratio.

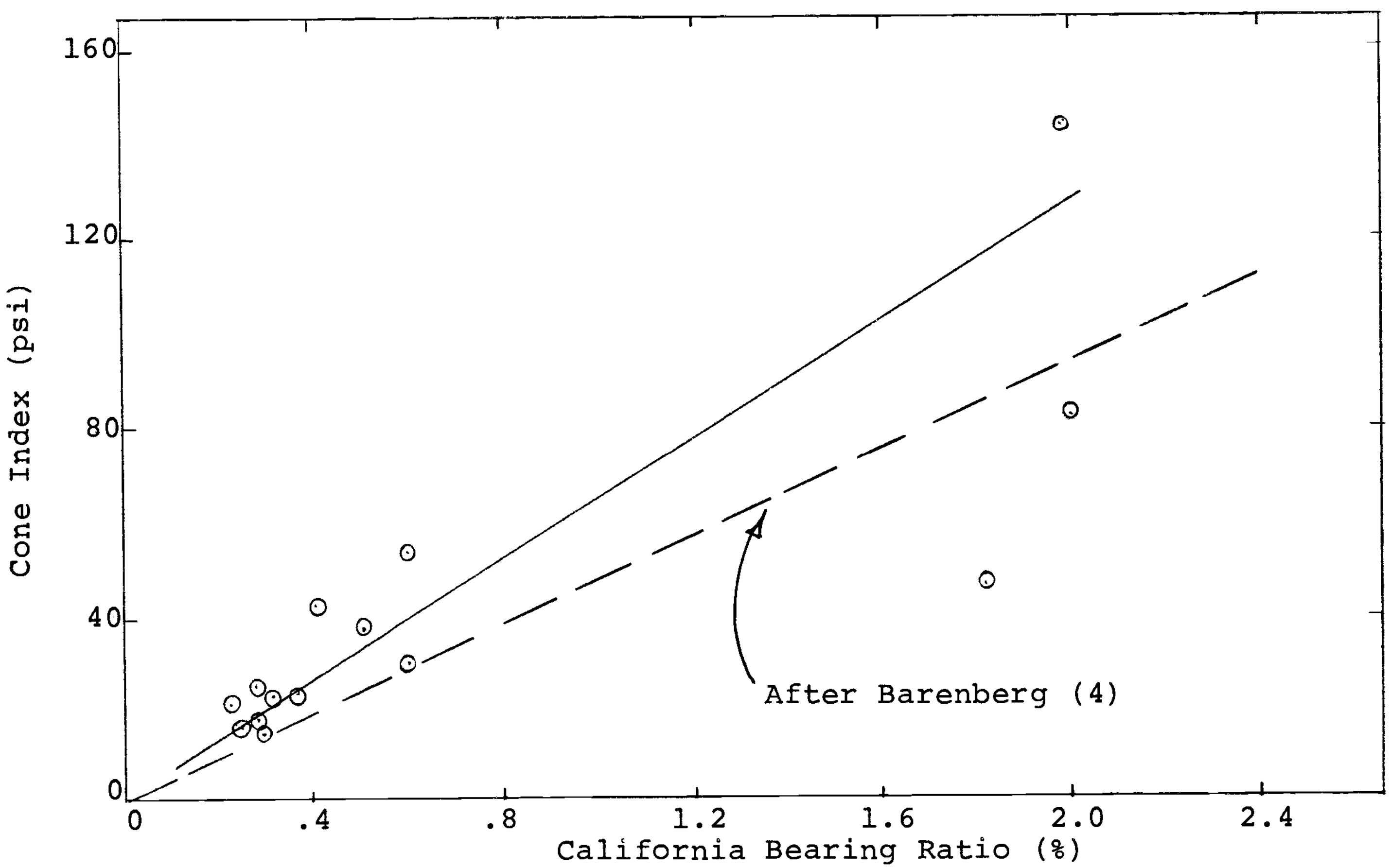


Figure 5.9. Relation between cone index and California Bearing Ratio.

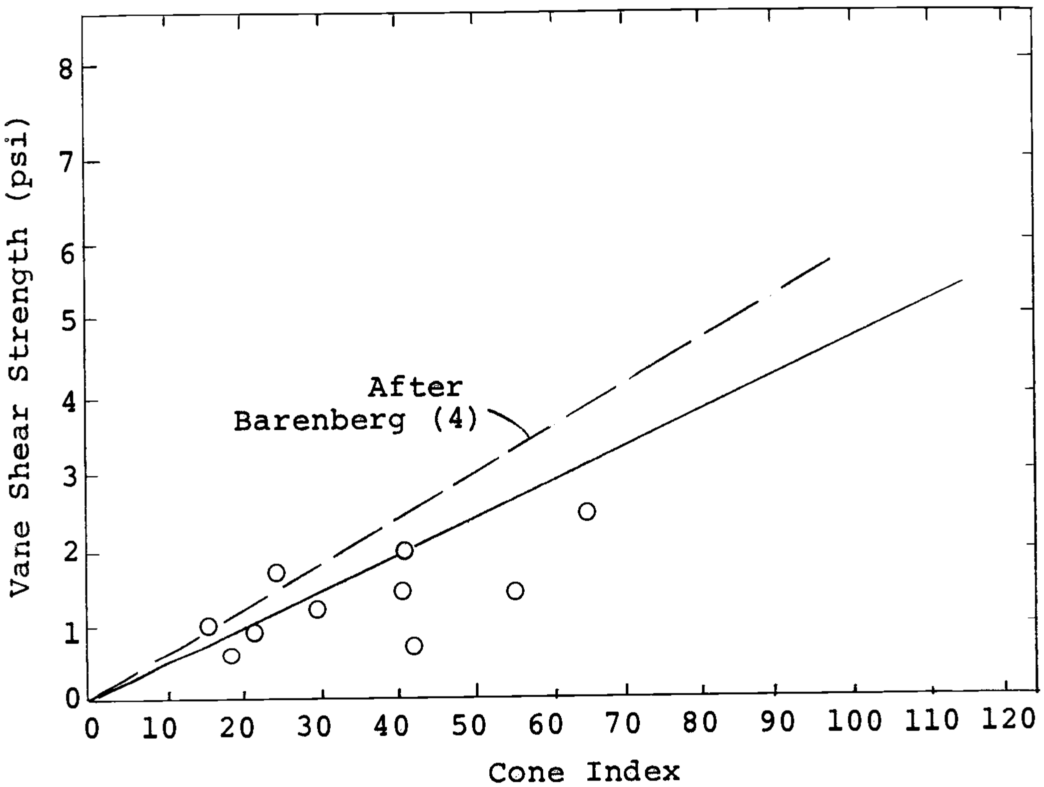


Figure 5.10. Relation between cone index and vane shear strength.

of the test load was 0.1 second and the frequency of the loading was 20 cycles per minute. The resilient modulus (M_R) was found from the relations:

$$M_R = \frac{\text{Deviator stress}}{\text{Resilient strain}}$$

Each test was performed by varying the deviator stress applied to the sample and recording the resilient strain. The confining pressure was kept constant at two psi. After the test, cone and Proctor penetrometer tests were performed on the samples.

The results of the tests are shown in Figures 5.11 and Table 5.4. The dynamic modulus obtained from the empirical

Table 5.4 Properties of subgrade soil.

	Density (lb/ft^3)	Moisture (%)	Cone index	Penetration Resistance (psi)	Average CBR	Es* (psi)
Test 1	125	27	42	51	.57	855
Test 2	119	29.3	28	38	.36	540

*Es = 1500 CBR.

correlation with CBR is indicated by the arrows in Figure 5.11. The dynamic modulus obtained empirically is slightly higher than the dynamic modulus obtained from the repeated triaxial test in the high deviator stress range.

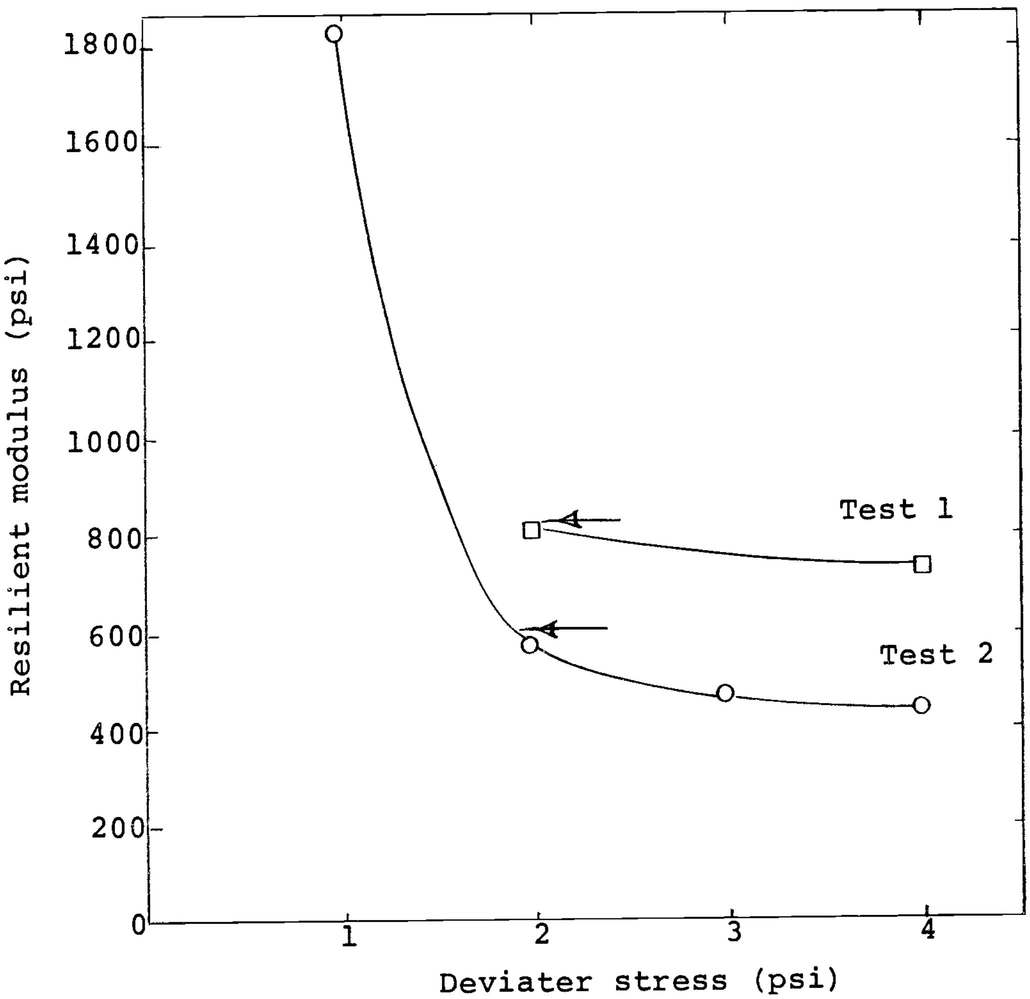


Figure 5.11. Resilient modulus (Mr) relations of the subgrade soil.

5.5.1.4 Properties of Fabric

There are several kinds of fabric on the market now. Only two kinds were selected for these tests. Fibretex 400, a needle-punched spundbonded polypropylene, and Mirafi 140, a heatbonded heterofilament nylon-polypropylene. Fabric tests included static as well as dynamic tests.

5.5.1.4.1 Static Tests of Fabrics

A strip tensile test was to evaluate the fabrics. A sample of four inches width was gripped at a spacing of two inches and loaded at a strain rate of 12 inches per minute (ASTM-1682). To see the environmental effect on the strength strength and elongation of fabric, the sample was tested in both wet and dry conditions. The test by both conditions yielded the same strength and elongation. Another effect that should be studied is that of temperature. Unfortunately, the equipment to control the temperature was not available; hence, the effect of temperature is not included in the test. The tests were performed at 75°F.

The fabrics tested are Fibretex 400 and Mirafi 140. The results of the test are shown in Table 5.5. Fibretex 400 has greater elongations. Typical load versus elongation curves are shown in Figure 5.12.

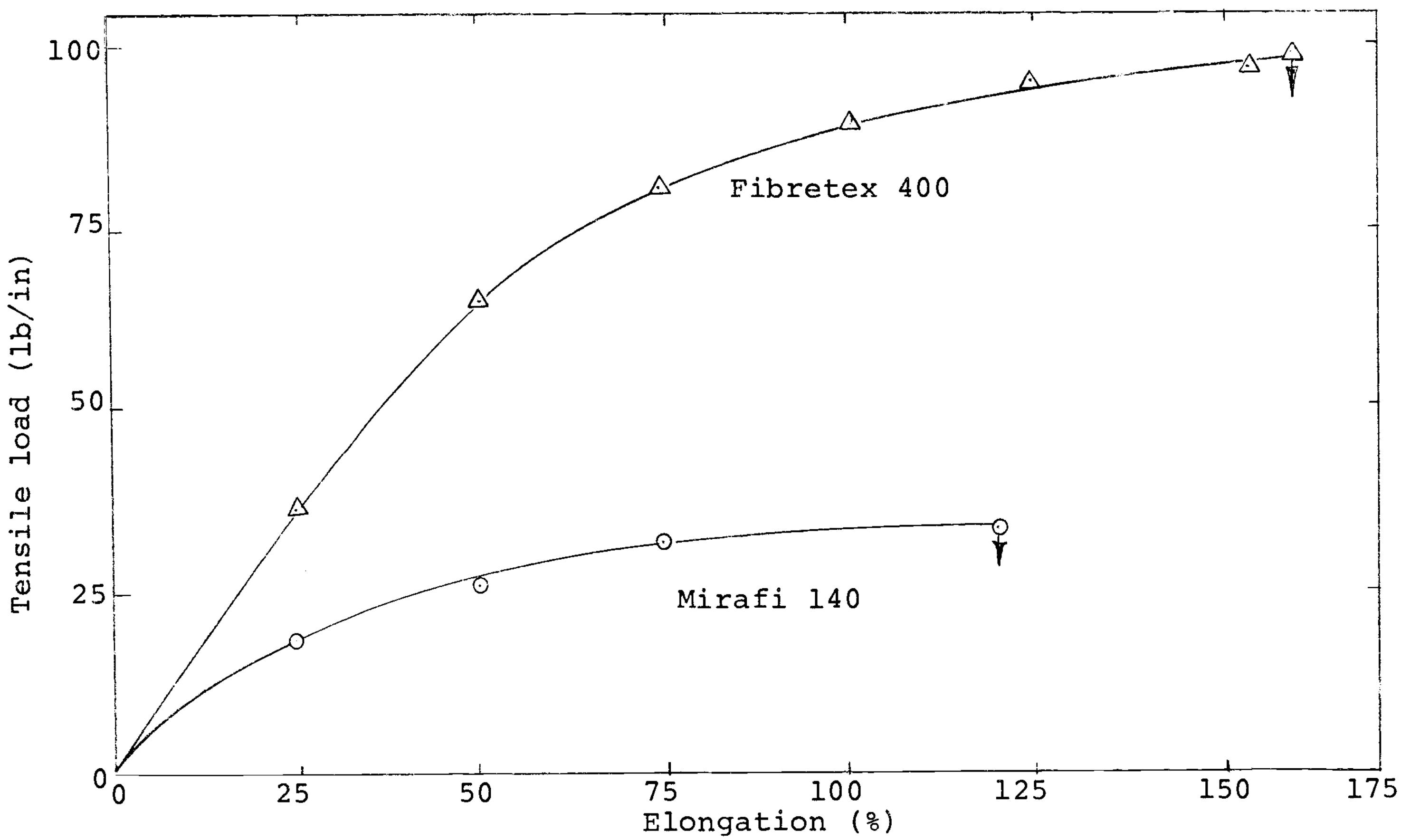


Figure 5.12. Typical load-elongation relations for fabrics.

Table 5.5. Fabric properties.

	Wet	Dry
<u>Fibretex 400</u>		
Tensile Breaking Load (lb/in)	99 97 average = 98	96 97 95 average = 96
Failure Elongation (%)	156 160 average = 158	149 158 152 average = 153
<u>Mirafi 140</u>		
Tensile Breaking Load (lb/in)	28	
Failure Elongation (%)	75	

5.5.1.4.2 Dynamic Properties of Fabrics

The dynamic properties of fabric are investigated using the same set-up as static tests. The load is applied a required number of repetitions with constant stress on each specimen. The machine used is a MTS system. The duration of the load is about 1.5 seconds with one to two seconds rest periods. The shape of load curve is about the same as Figure 5.4, though tension was applied instead of compression.

The relationship between the deformation of the fabric and the number of repetitions of the load is shown in Figure 5.13 for Fibretex 400. The relationship between resilient modulus and deviator stress is shown in Figure 5.14 for both fabrics. The resilient modulus is

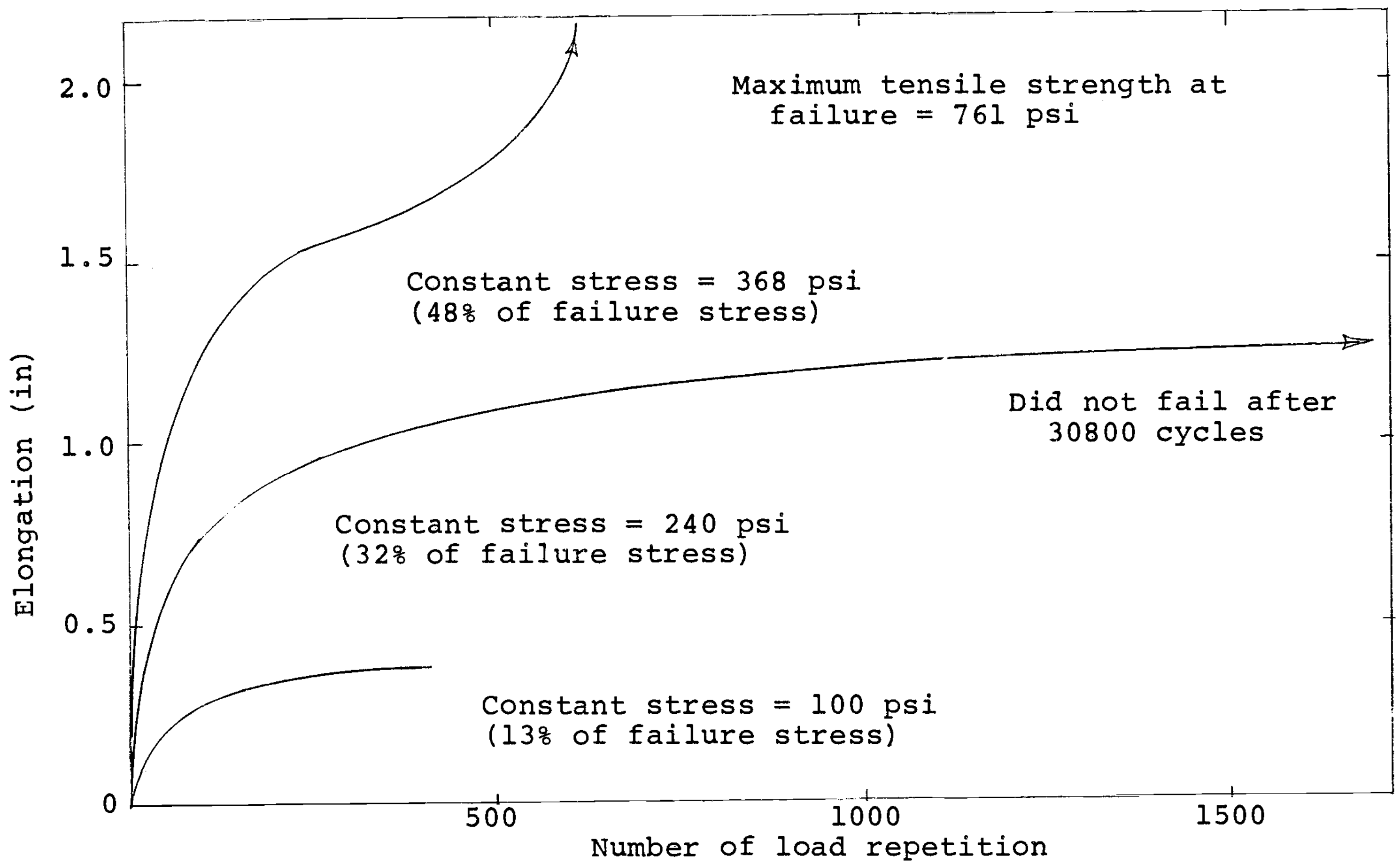


Figure 5.13. Relation between elongation and number of load repetitions

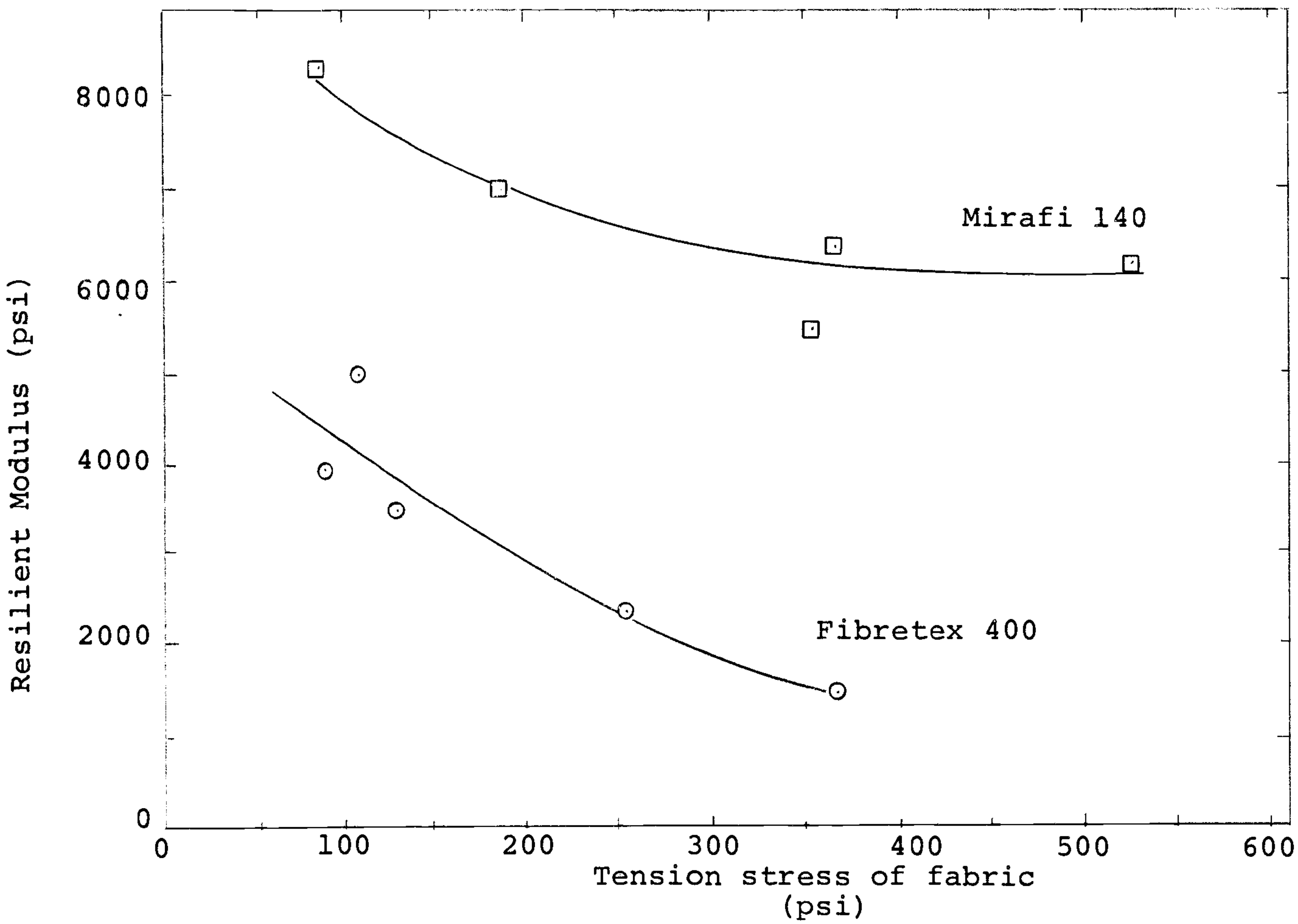


Figure 5.14. Relation between resilient modulus and tension stress of fabrics.

defined as tensile stress divided by resilient tensile strain.

To see the effect of tensile stress on the modulus of the fabric, three load tests were applied to the Fibretex fabric as shown in Figure 5.13. The first test applied a stress approximately 1/10 of the tensile strength of fabric. The second test applied a stress about 1/3 of the strength of fabric. The fabric did not fail after 30,800 of these load applications. In the test when the load was 48 percent of the strength of the fabric, the fabric failed by fatigue at 600 applications of load. Figure 5.14 shows the relation between the resilient modulus of Fibretex and Mirafi and the tensile stress applied. The modulus decreased as the tensile stress increased and varies between 1500 and 5000 psi for Fibretex. The values are considerably higher for Mirafi, but since it is much thinner, its reinforcing effect is less than that of Fibretex.

Based on the limited number of tests shown above, the resilient deflection appears to be the same for all number of load applications when the stress applied is less than half of the tensile strength of the fabric.

The temperature effect is not considered though the service temperature is likely to vary over a wide range. Further investigations should attempt to study the effects of temperature change on static and dynamic properties of fabrics. The results from the static tests performed by

Mark (1), discussed in Chapter 3, show that the failure elongation of fabric at -50°C is lower than at room temperature and the strength of both conditions are the same. This implies that the modulus of a fabric is likely to be higher at low temperatures than at high temperatures.

5.5.1.5 Granular Materials

The granular material used in these tests was dense graded, medium gravel. The grain size distribution is shown in Figure 5.6. The static test used on the granular materials is the CBR test. The density of the granular surface course was controlled by compacting with different compactive efforts from no compaction to Standard AASTHO for the CBR tests. The dry density was between 102-118 lb/ft^3. The moisture content was about four to five percent. The test results are in Table 5.6. The CBR ranged from 7.8 to 44.4 percent.

Table 5.6. CBR of granular base.

Moisture Content (%)	Dry Density (lb/ft^3)	CBR (%)
4.7	102.2	7.8
4.6	104.2	14.6
4.2	112.2	27.1
4.0	118.2	44.4

The dynamic tests were performed using a procedure recommended by Kalcheff and Hicks (28) to determine resilient modulus of granular materials. Two samples were prepared to the densities in the model tests. The dry densities were 104 and 115 pounds per cubic foot. The moisture content was about five percent. The results of the test are shown in Figure 5.15. The resilient modulus ranged from 1200 $\theta^{0.6}$ to 2000 $\theta^{0.6}$ psi. These values are compared to values obtained by several investigators in Table 3.2 (Chapter 3). They are less than the values obtained by the other investigators. This is probably because the compaction method used in the tests resulted in very low densities.

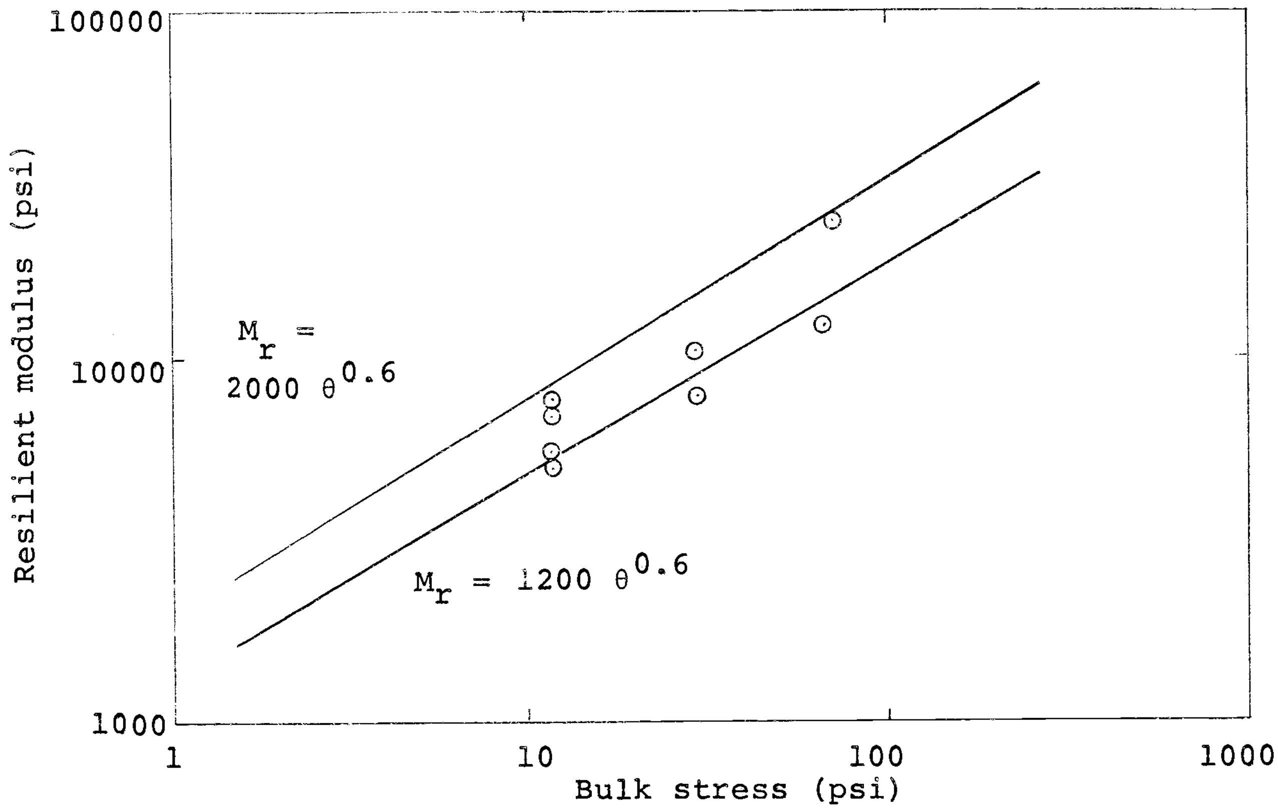


Figure 5.15. Relation between resilient modulus and bulk stress of granular materials.

VI. RESULTS AND DISCUSSIONS

A general description of the properties of soil materials in the tank and the results obtained from the load tests are summarized in the first part of this chapter. The discussion of test results are in the second part of the chapter.

6.1 Test Results

The properties of materials in the test section are presented in Table 6.1. Moisture, density, cone index and penetration resistance are recorded before and after the test. CBR, shearing strength and dynamic modulus are taken from the relations mentioned in Chapter V. The dry density of the granular surface is 89.2-117.6 pounds per cubic foot with an average of 102.8 pounds per cubic foot. The moisture content of the subgrade soil is 23.6-35.8 percent which are divided into two groups. One is the stiffer subgrade with CBR greater than one. These have water contents of about 25 percent and less. The other is of softer subgrades with CBR less than one. These have water contents greater than about 30 percent. The same is true for cone index and penetration resistance for stiffer subgrade which are 100 and 150 psi, respectively, and for softer subgrade are 20 and 50 psi.

Table 6.1. Properties of materials in test sections.

Property	Time	Soil	Test Number I.A	I.B	I.C	II	III.A	III.B
Moisture	before load	surface	4.4	4.0	4.36	3.0	3.8	3.3
		subgrade	28.3	27.6	23.6	29.4	32.4	32.9
	after load	surface	4.05	3.74	3.5	--	3.8	5.2
		subgrade	29.5	27.7	25.5	29.0	29.8	32.1
Wet Density (lb/ft^3)	before load	surface	116.8	113.4	122.8	107	119.8	103.0
		subgrade	112.8	106.6	110.8	119.0	126.6	124.0
	after load	surface	115.1	112.2	120.8	119.2	114.2	115.0
		subgrade	92.8	122.6	94.2	110.0	112.3	114.0
Dry Density (lb/ft^3)	before load	surface	111.8	109.0	117.6	103.8	115.4	99.7
		subgrade	93.8	83.5	89.6	92.1	95.6	93.3
	after load	surface	110.6	108.1	116.7	114.6	110.0	109.3
		subgrade	90.8	83.4	75.0	85.2	86.5	86.2
Cone Index (psi)	before load	subgrade	60.0	82.4	96.4	78.0	27.0	22.8
	after load	subgrade	85.2	110.8	109.0	97.0	50.4	22.0
Penetration Resistance (psi)	before load	subgrade	102.0	160.4	147.6	146.8	52.0	26.0
	after load	subgrade	138.0	173.6	184.0	183.0	58.0	37.0
CBR (%)	before load	subgrade CI*	.92	1.50	1.60	1.30	.45	.38
		subgrade PR**	1.00	1.45	1.30	1.30	.47	.23
	after load	subgrade CI*	1.25	1.90	1.95	1.60	.84	.37
		subgrade PR**	1.20	1.55	1.65	1.65	.53	.37
	average	subgrade	1.1	1.6	1.6	1.5	.57	.34
Modulus (psi)	average	subgrade	1650.0	2400.0	2400.0	2250.0	855.0	510.0
Shear Strength (psi)	average	subgrade	8.34	11.1	11.8	10.0	4.3	2.4

*CBR correlation with Cone Index; **CBR correlation with Penetration Resistance.

Table 6.1 (continued)

Property	Time	Soil	III.C	IV	V	VI.A	VI.B	VI.C
Moisture	before load	surface	4.6	4.0	4.0	3.0	4.0	5.1
		subgrade	31.9	30.8	30.6	31.1	31.6	32.3
	after load	surface	4.3	3.0	4.4	3.0	3.0	4.3
		subgrade	30.2	30.1	29.4	31.7	29.3	31.3
Wet Density (lb/ft^3)	before load	surface	105.0	109.2	106.7	92.3	104.0	109.0
		subgrade	128.8	116.5	113.5	115.0	122.0	105.5
	after load	surface	100.5	113.9	96.7	92.0	99.1	94.0
		subgrade	102.2	111.2	110.4	108.0	111.0	128.6
Dry Density (lb/ft^3)	before load	surface	100.3	105.0	102.5	89.6	100.0	103.7
		subgrade	97.6	89.0	86.9	76.2	92.7	79.7
	after load	surface	96.3	110.0	92.6	93.2	96.2	90.3
		subgrade	78.4	85.54	85.3	82.4	85.8	97.9
Cone Index (psi)	before load	subgrade	240	26.0	28.0	25.0	13.0	26.0
	after load	subgrade	31.0	36.7	40.0	--	20.0	24.0
Penetration Resistance (psi)	before load	subgrade	26.0	35.0	37.0	44.0	31.0	32.0
	after load	subgrade	39.0	39.0	48.0	--	35.0	26.0
CBR (%)	before load	subgrade CI*	.4	.43	.49	.2	.22	.31
		subgrade PR**	.27	.32	.37	--	.29	.32
	after load	subgrade CI*	.51	.60	.67	.4	.33	.26
		subgrade PR**	.35	.36	.44	--	.32	.28
	average	subgrade	.38	.43	.49	.3	.29	.3
Modulus (psi)	average	subgrade	570.0	645.0	735.0	450.0	435.0	450.0
Shear Strength (psi)	average	subgrade	2.7	3.4	3.8	2.8	2.1	2.9

*CBR correlation with Cone Index; **CBR correlation with Penetration Resistance.

Table 6.1 (continued)

Property	Time	Soil	Test Number VII.A	VII.B
Moisture	before load	surface	4.0	4.5
		subgrade	28.0	28.0
	after load	surface	3.6	5.3
		subgrade	--	30.0
Wet Density (lb/ft^3)	before load	surface	102.0	120.1
		subgrade	114.4	125.5
	after load	surface	92.5	103.8
		subgrade	109.9	109.3
Dry Density (lb/ft^3)	before load	surface	98.0	114.9
		subgrade	89.3	98.6
	after load	surface	89.2	98.5
		subgrade	85.8	84.0
Cone Index (psi)	before load	subgrade	30	32
	after load	subgrade	44	44
Penetration Resistance (psi)	before load	subgrade	31	--
	after load	subgrade	48	--
CBR (%)	before load	subgrade CI*	--	.44
		subgrade PR**	--	--
	after load	subgrade CI*	--	.44
		subgrade PR**	--	--
	average	subgrade	.42	.44
Modulus (psi)	average	subgrade	621.0	652.0
Shear Strength (psi)	average	subgrade	3.46	3.69

*CBR correlation with Cone Index; ** CBR correlation with Penetration Resistance.

The moisture contents of the granular surface materials and subgrade soils before and after loading remain about the same. The density of granular materials shows variations after loading, though there is no consistent pattern. This is also true of the subgrade density. The cone index and penetration resistance after loading are higher than before loading in all cases. An explanation may be that some compaction takes place during loading.

The relation of the rut depth in the surface and the number of load applications of all the tests with Fibretex is plotted on an arithmetic scale in Figure 6.1. The rate of increase of rut is considerable with the initial load applications. Then there is a gradual decrease as the number of load applications increases. This is better illustrated on a semi-log scale. Figures 6.2 through 6.6 show the relations of rut depth in both surface and subgrade with respect to the number of load applications on a semi-log scale. The decrease in thickness of the granular surface during loading can also be determined by subtracting rut in subgrade from the rut at surface.

The results of the model tests on stiffer subgrade (CBR > 1) are shown in Figure 6.2. Different thicknesses of base of 20 inches, 15 inches and 12 inches are used on the stiffer subgrade with Fibretex 400 fabric in Test I. Test II was without fabric. The rate of increase of rut with and without fabric for the same 15 inches thickness

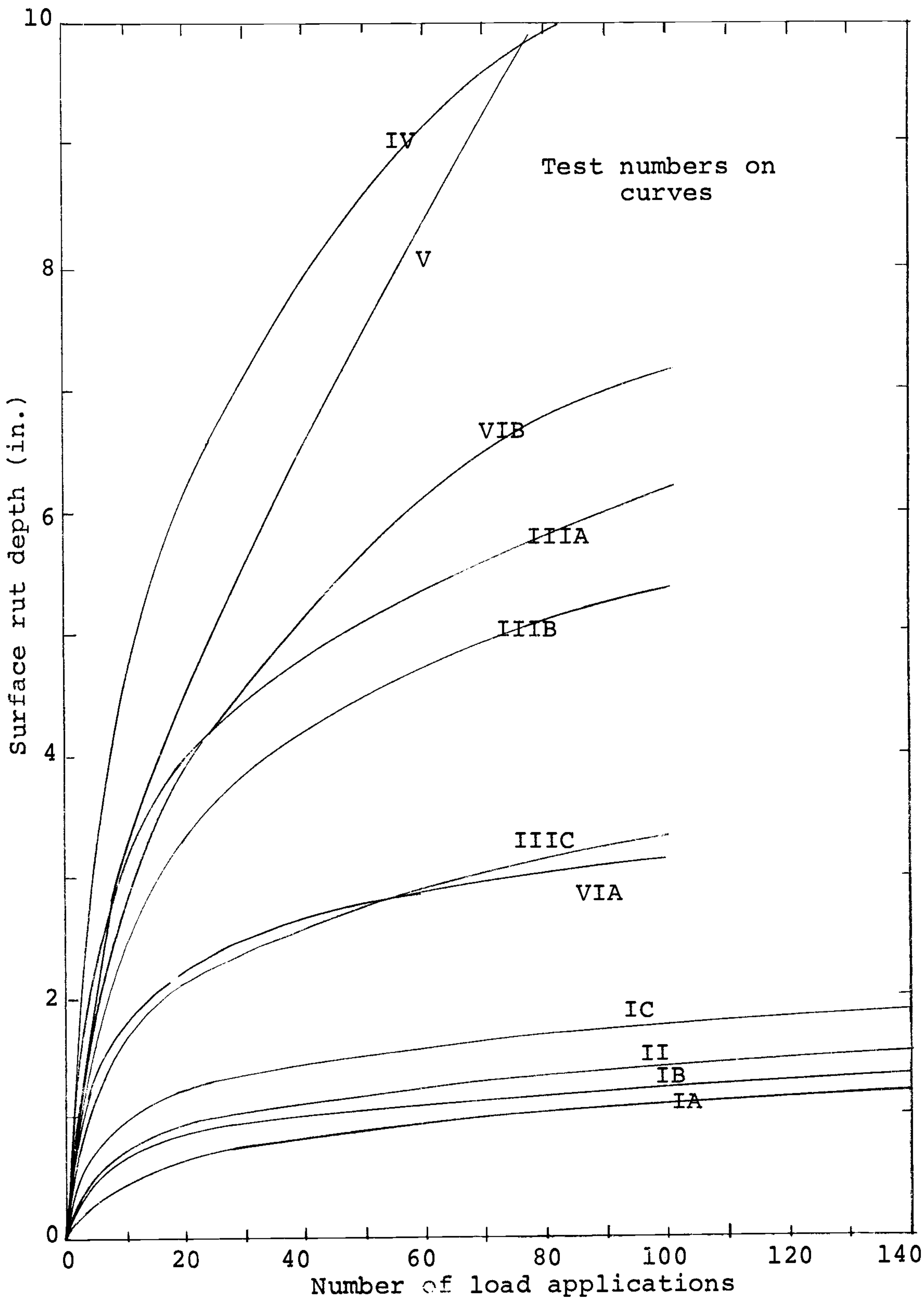


Figure 6.1. Surface rut depth versus number of load applications.

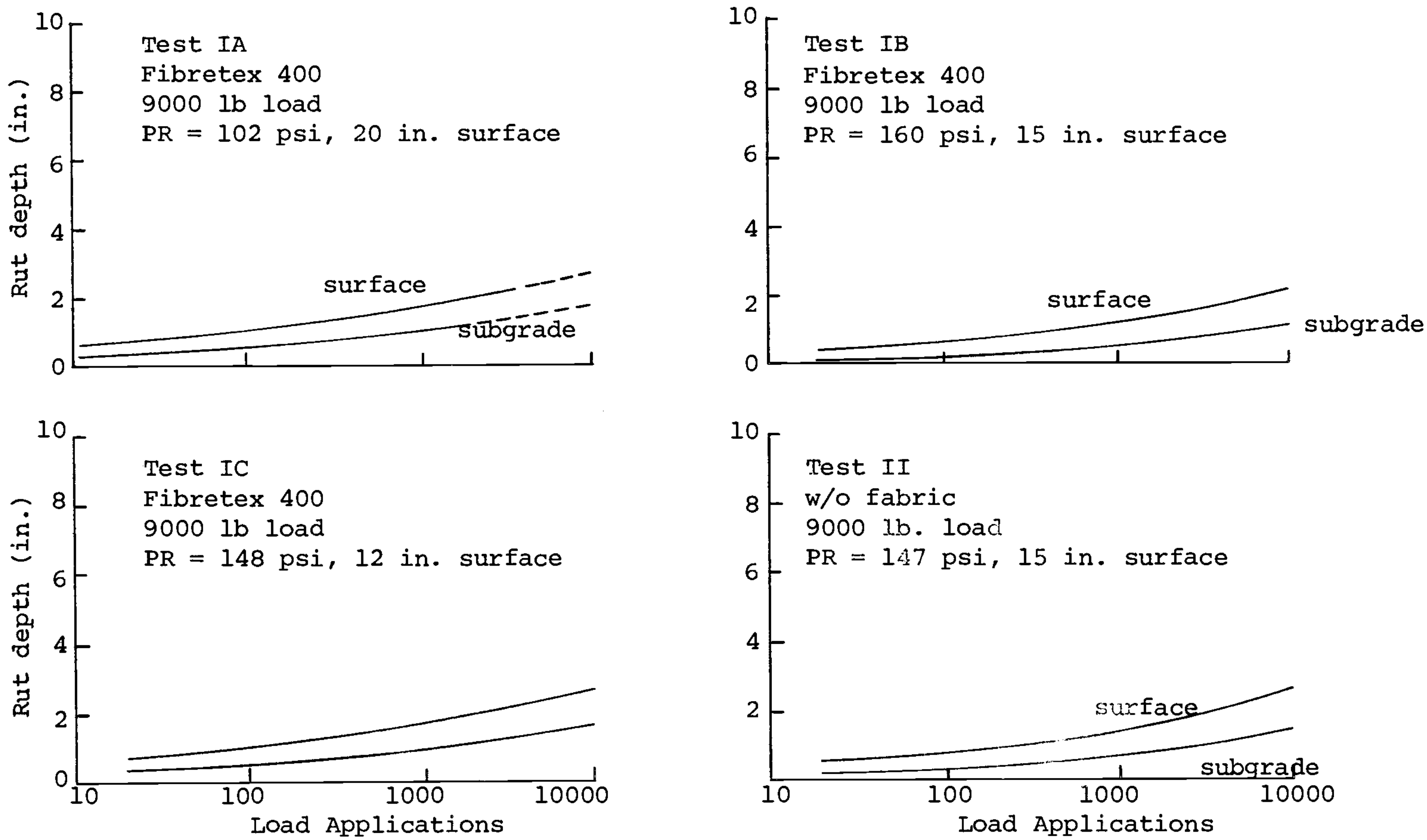


Figure 6.2. The relation between rut depth and number of load applications on stiff subgrade (CBR > 1) with varying surface thickness.

is about the same. The rate of rut in the system with a greater thickness of base is lower than the rate of rut in a smaller thickness of base.

The results of tests with loads of 9000, 5000 and 3000 pounds are plotted in Figure 6.3. The thickness of base is 10 inches in all cases. The rate of rutting is higher with the larger loads.

The results of tests with surface thicknesses of 10 to 20 inches on soft subgrades with fabric are presented in Figure 6.5. For the Mirafi 140 fabric the results are in Figure 6.6. The system with Mirafi fabric has a higher rate of rut than the system of Fibretex 400. Mirafi was tested to allow comparison with the results of Barenberg, et al. (4) who used this fabric in his tests.

The elastic deflections for all tests are presented in Table 6.2. In most cases the elastic deflection is lower as the number of load applications increases. This may be due to the compaction that takes place. However, the elastic deflection increases as the number of load applications increases when a 10 inch base on a soft subgrade is subjected to a load of 9000 pounds. This might be due to the movement in the granular surface during loading, causing a decrease in thickness of the granular surface and resulting in a higher stress in subgrade. This can be noted from the cross section of the system before and after the test. The

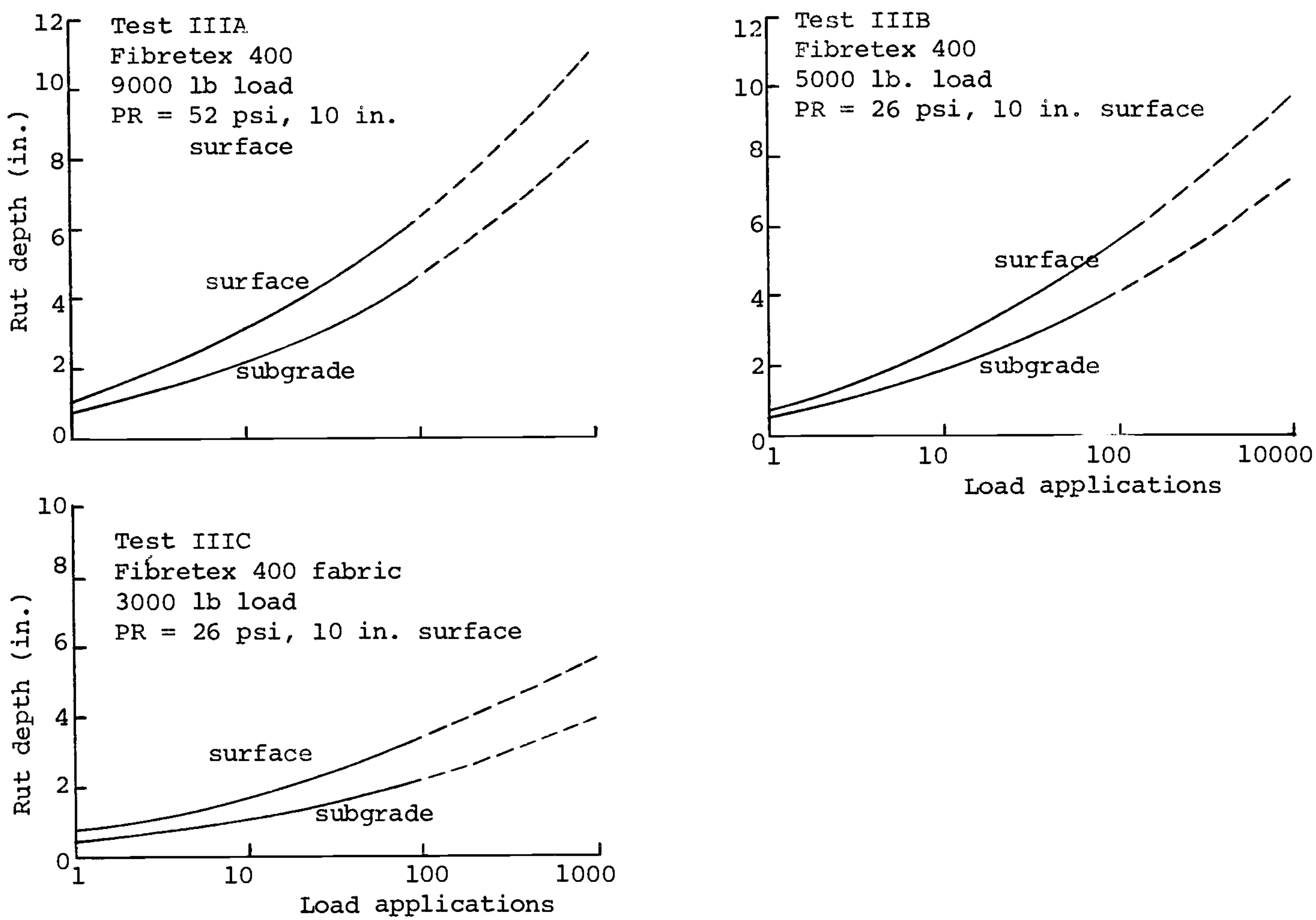


Figure 6.3. The relation between rut depth and number of load applications on soft subgrade (CBR < 1) with varying load.

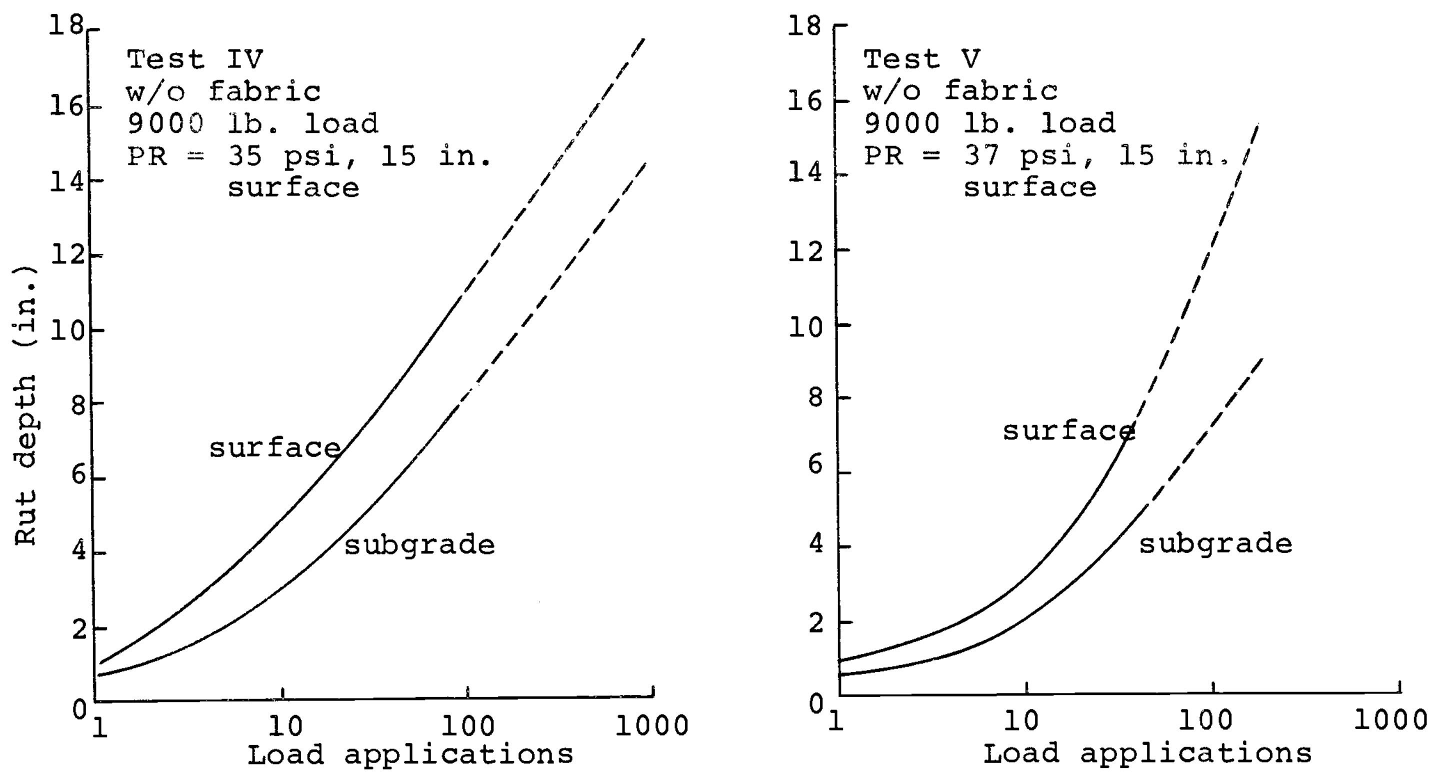


Figure 6.4. The relation between rut depth and number of load applications without fabric on soft subgrade (CBR < 1).

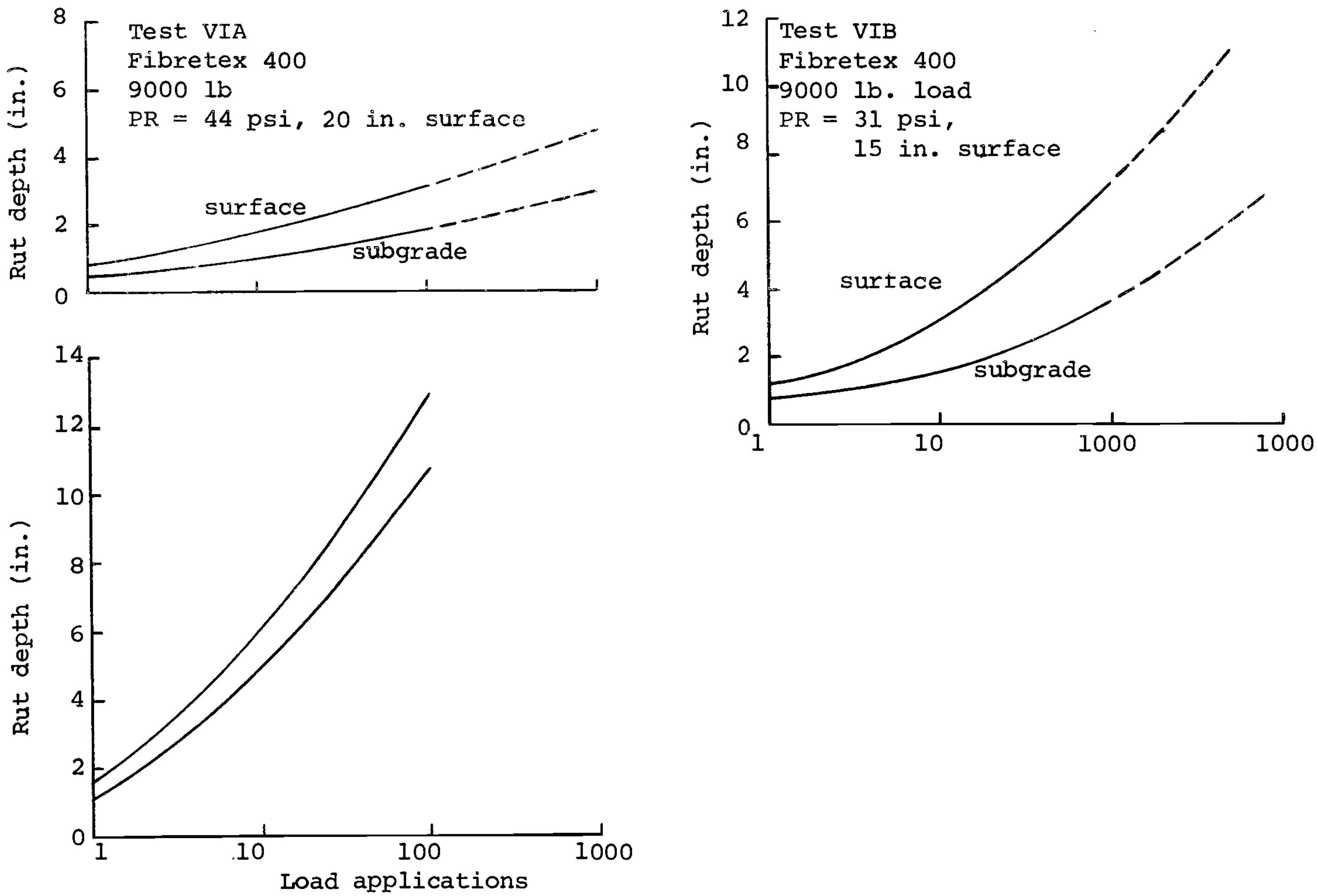


Figure 6.5. The relation between rut depth and number of load applications with fabric on soft subgrade (CBR < 1) with varying surface thickness.

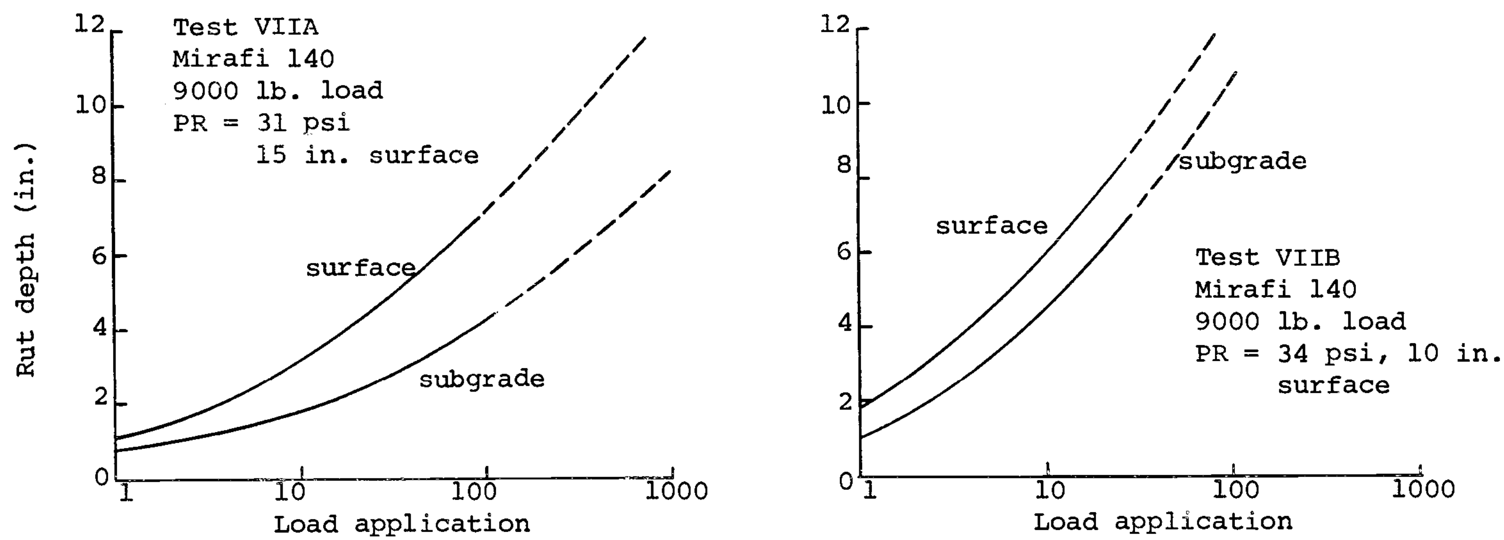


Figure 6.6. The relation between rut depth and number of load applications with Mirafi 140 fabric on soft subgrade (CBR < 1) with varying surface thickness.

Table 6.2. Elastic deflections of surface and subgrade in inches.

Test I.A			Test I.B			Test I.C			Test II		
load no.	surf. δ	sub δ	load no.	surf. δ	sub δ	load no.	surf. δ	sub δ	load no.	surf. δ	sub δ
7	.178	-	2	.175	-	2	.226	-	2	.150	-
81	.150	-	11	.172	-	16	.183	-	11	.130	-
500	.108	-	100	.144	-	96	.190	-	98	.123	-
1002	.110	-	600	.135	-	540	.175	-	581	-	-
2000	.101	-	1000	.132	-	1000	.156	-	1000	.108	
Test III.A			**Test III.B**			**Test III.C**			**Test IV**		
load no.	surf. δ	sub. δ	load no.	surf. δ	sub δ	load no.	surf. δ	sub δ	load no.	surf. δ	sub δ
5	.400	-	6	.534	-	2	.445	.325	11	.495	.375
10	.424	-	10	-	.370	10	.380	.335			
33	.377	.360	16	.550	.420	30	.300	.256			
			31	.630	.540						

Table 6.2 (continued)

Test V			Test VI.A			Test VI.B			Test VI.C		
load no.	surf. δ	sub. δ	load no.	surf. δ	sub. δ	load no.	surf. δ	sub. δ	load no.	surf. δ	sub. δ
2	.461	.258	2	.320	–	5	.526	.460	5	.760	.680
17	.456	.283	11	.330	.216	30	.520	.300	6	.890	.725
			52	.311	.180						
			100	.220	.165						
			800	.193	.165						

Test VII.A			Test VII.B		
load no.	surf. δ	sub. δ	load no.	surf. δ	sub. δ
3	.590	.525	6	.880	.740
8	.528	.480			
30	.519	–			

thickness of granular base after loading is smaller than before loading.

The profiles of the test sections before and after loading are shown in Figure 6.7. This shows that some permanent deformation occurred in the granular surface and subgrade. None of the fabric failed during the testing. When the depression shape in the system with a softer subgrade without the fabric is compared to the system with the fabric, the shape of the depression with fabric seems to be smoother at the edge of the depression. But in case of stiffer subgrade, the depression shape is about the same for both systems. The heave of the subgrade material was also noticed in most of the test cases on the very soft subgrade. The depression shapes of the test sections agree well with the elastic deflections calculated by finite element method shown in Chapter 7.

6.2 Discussion of the Results

The thickness, magnitude of the load and properties of the subgrade are different for the various test sections. In order to compare the effects of fabric, the elastic theory is used. As discussed earlier, the Boussinesq theory is simple to use and calculates vertical stresses close to measured values. For an approximation to see if the use of fabric does seem to be beneficial, the Boussinesq theory is selected. This theory is used to account for

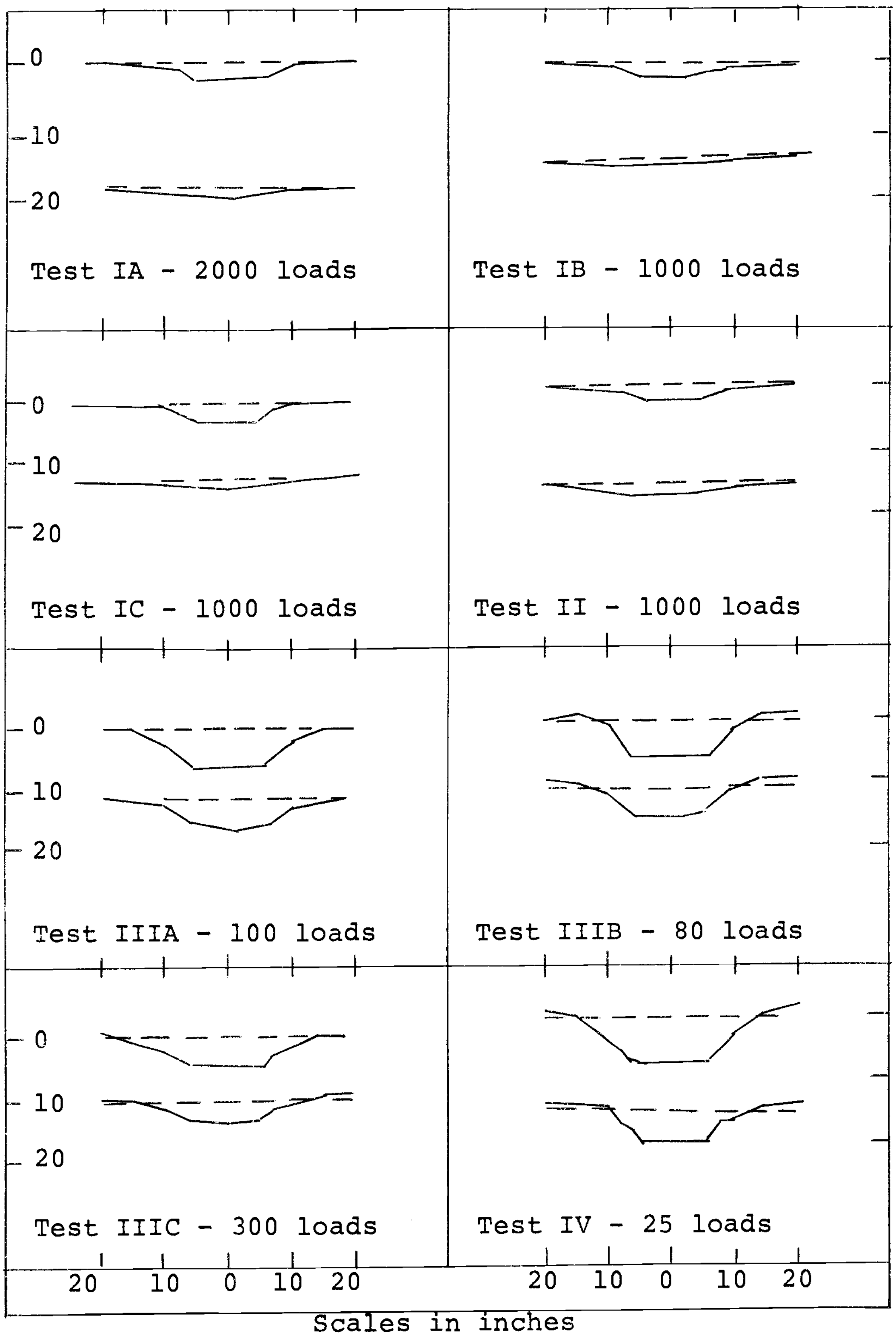


Figure 6.7(a). Profiles of test sections before and after loading.

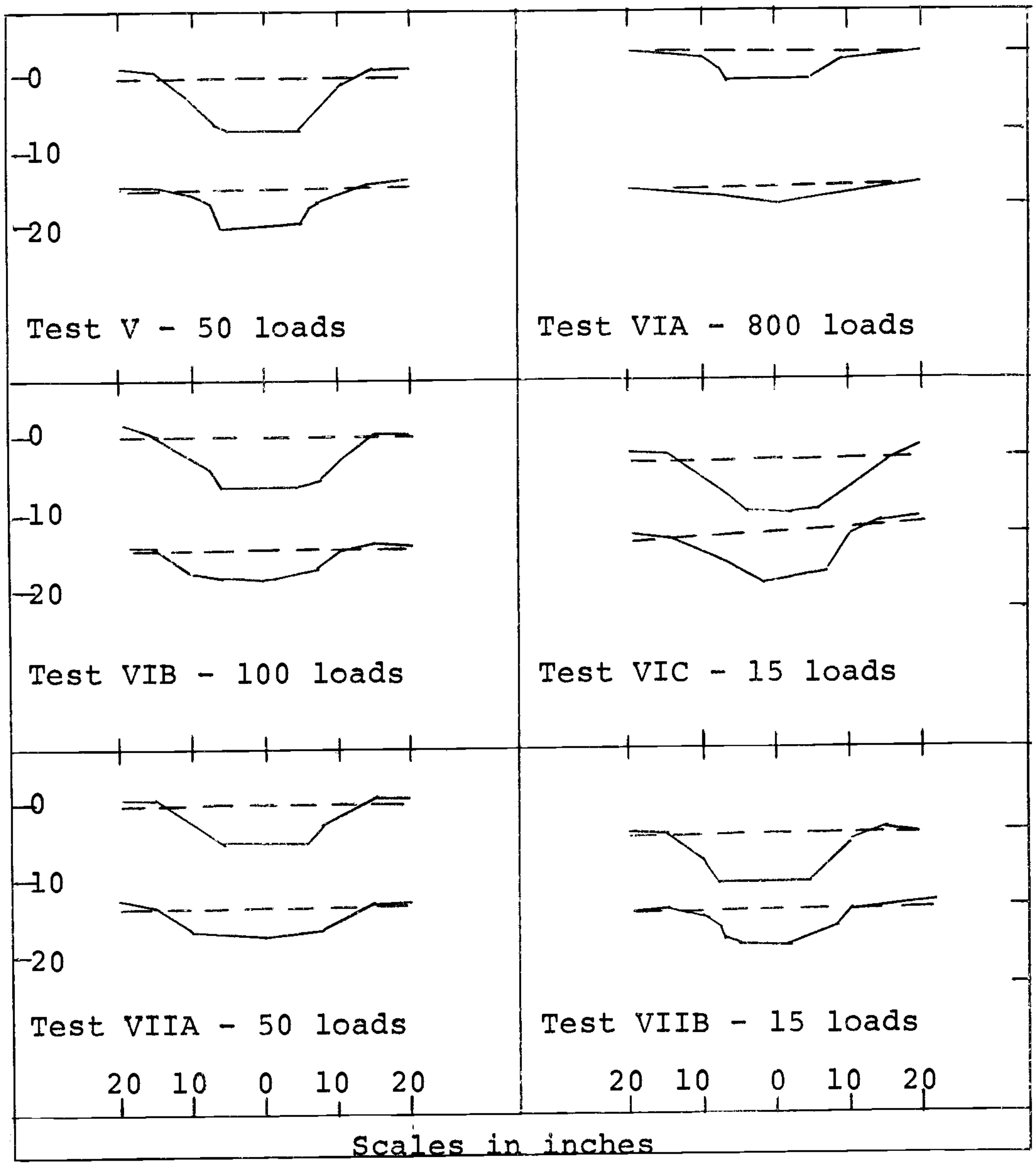


Figure 6.7(b). Profiles of test sections before and after loading.

pressure, thickness of granular surface course and size of plate. The following relation is used to solve the vertical stress on subgrade (47)

$$\sigma_2 = P[1 - (\frac{Z}{(R^2 + Z^2)})^3]$$

where: P = contact pressure

R = radius of load area

Z = thickness of granular base

To take into account subgrade properties, the stresses on subgrade are divided by strength of subgrade in terms of shearing strength or a strength index such as cone index or penetration resistance. Since the rut depth of surface and rut depth in subgrade are both significant in pavement design, the relations between the rut in the subgrade and in the surface and the ratio of stress to strength of the subgrade soil will be established. These relations can be used as a basis of comparison for the behavior of roadways with and without fabric so that an evaluation of the fabric can be made.

The relations between the ratio of vertical stress on subgrade to penetration resistance and the ruttings have the best correlation. These relations are shown in Figure 6.8. In both the rut depth corresponds to 100 load applications.

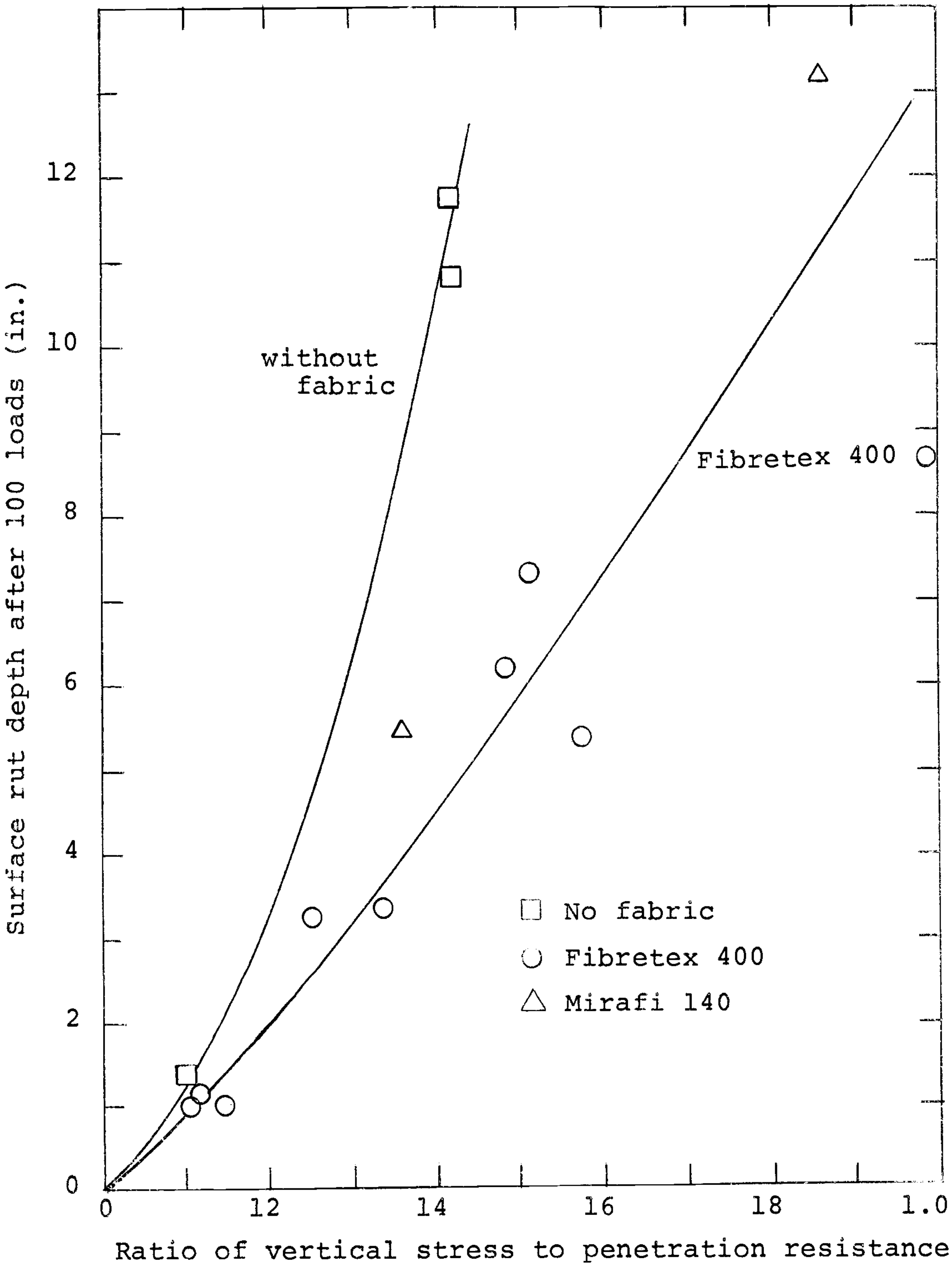


Figure 6.8(a). The relation between surface rut and ratio of vertical stress on subgrade to penetration resistance.

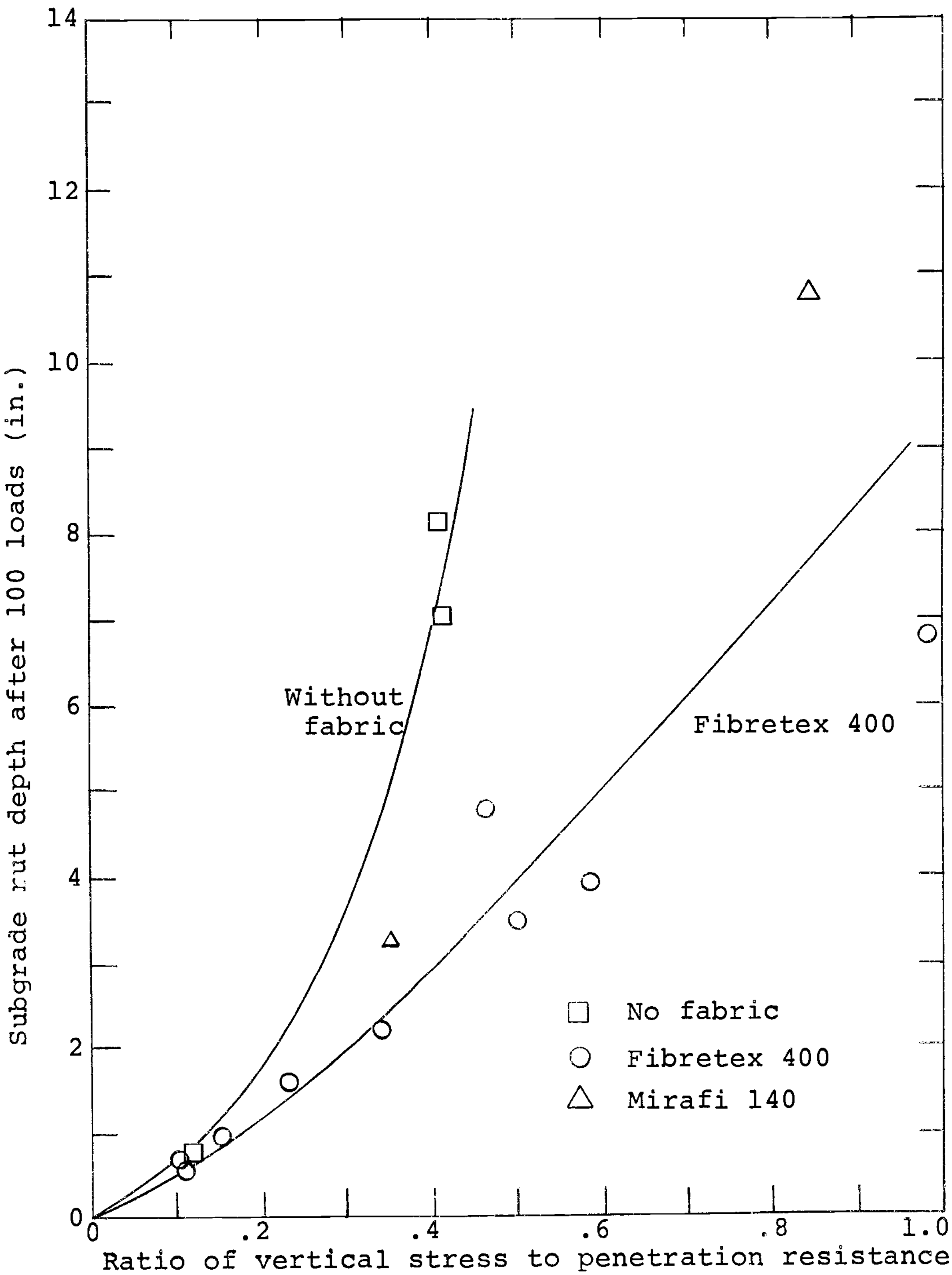


Figure 6.8(b). The relation between subgrade rut and ratio of vertical stress on subgrade to penetration resistance.

6.2.1 The Effect of Magnitude of Load and Size of Load

The Boussinesq theory adequately accounts for the effects of load, gravel thickness, and radius of plate. This is shown in Figure 6.8 where the correlation is good even though the load and thicknesses of gravel layer are varied.

The relations from Figure 6.8 are also compared to the results of Barenberg _et al_. (4) in Figure 6.9. Barenberg's original relation is relative to the ratio of vertical stress on subgrade to shearing strength. To prepare Figure 6.9, shearing strength has been converted to penetration resistance, using the relations developed in Chapter 5.

The rate of rutting for Barenberg's tests is higher than that from the system using Fibretex 400 in this investigation. This could be explained by two reasons. First, the granular materials of Barenberg's experiment were open-graded, granular materials, while in our experiment, dense-graded, granular materials were used. Usually, the surface of open-graded materials tend to have less stability and yield a higher rate of rutting in a granular surface than the system with dense-graded materials. Second, in the prediction of the rate of rutting at 100 load applications, Barenberg, _et al_. (4) extrapolated the rut depth on an arithmetic scale. In our test, some of the necessary points were extrapolated using a semi-log scale. The rut predicted from extrapolation on a semi-log scale seems to be more accurate. This predicted rate of rutting is lower

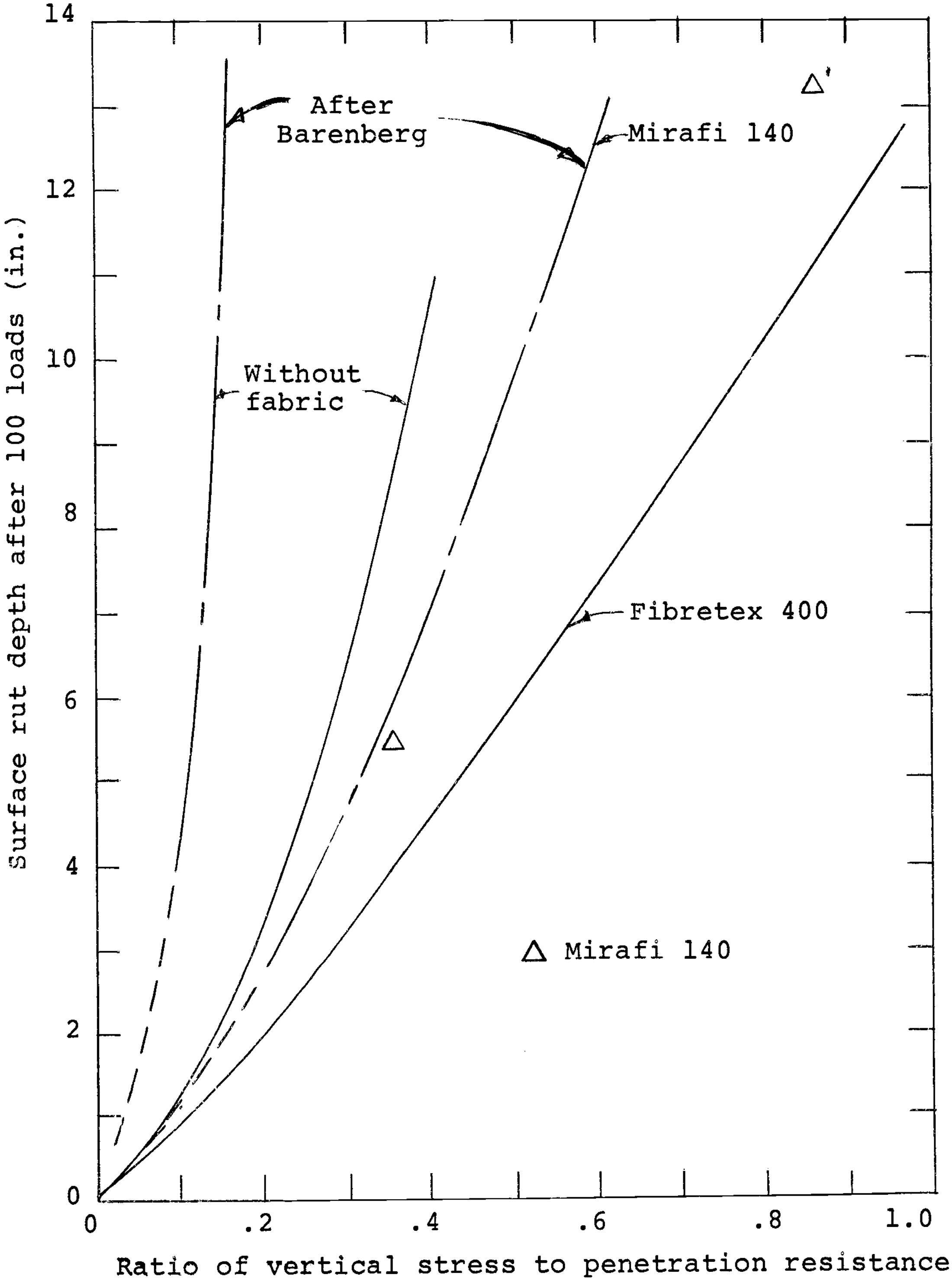


Figure 6.9. The relation between rut depth in surface and the ratio of vertical stress on subgrade to penetration resistance compared to results of Barenberg et al. (4).

than when the arithmetic scale is used. It also should be noted that several conditions were varied by Barenberg et al. (4) (i.e. magnitude of load, size of load and thickness of granular surface) and these results show that the Boussinesq theory adequately accounts for these conditions.

6.2.3 The Effect of Subgrade Strength

The effect of subgrade properties has been taken into account by using the ratio of vertical stress on the subgrade and the strength of subgrade. In Figure 6.8 the ratio of the vertical stress on subgrade to penetration resistance is used for all test sections and the correlation is satisfactory. When tests with Fibretex 400 fabric are considered a good correlation is obtained.

6.2.4 The Effect of Types of Fabric Used

The curve of the relations between the ratio of vertical stress on subgrade to penetration resistance for Fibretex fabric is obtained from nine model tests. When Mirafi 140 is used, the rate of rutting is higher than for Fibretex 400 fabric for the same ratio of vertical stress on the subgrade to penetration resistance. It should be noted that only two tests were actually performed on Mirafi 140. However, the tests compare well to the results with Mirafi 140 obtained by Barenberg, et al. (4) in Figure 6.9. The higher rate of rutting with Mirafi 140 could be explained in terms of equivalent modulus discussed previously. The thickness of Mirafi 140 is about four times less than Fibretex 400. Therefore, the effective resilient modulus of Mirafi 140 is about half of Fibretex 400. It should be further noted that the total tensile strength of the fabric seems to have the most influence on the behavior of the system incorporating the fabric layer and Mirafi 140 has less than half the ultimate strength of Fibretex 400.

6.2.5 Effect on Number of Load Applications

The effect of number of load applications has been shown earlier in Figures 6.2 to 6.6. The rut depth increases rapidly with the first few load applications and then increases at a slower rate. It increases with a slight upward curve on the semi-log scale.

6.3 Conclusions

The effects of subgrade strength, magnitude of load, and thickness of gravel surface are adequately taken into account by the Boussinesq theory. The fabrics are potentially beneficial when the ratio of vertical stress on subgrade to penetration resistance is high. Usually this condition will be encountered only on a very soft subgrade.

Although the use of the Boussinesq theory to develop the relations between the ratio of vertical stress on subgrade to penetration resistance of soil and rut depth will be convenient in evaluating the conditions of potential use of fabrics and to approximate the rutting of the subgrade, the properties of the granular materials and of the fabric are not considered by this theory. However, a theory that can take these properties into account is available and is investigated in the next chapter.

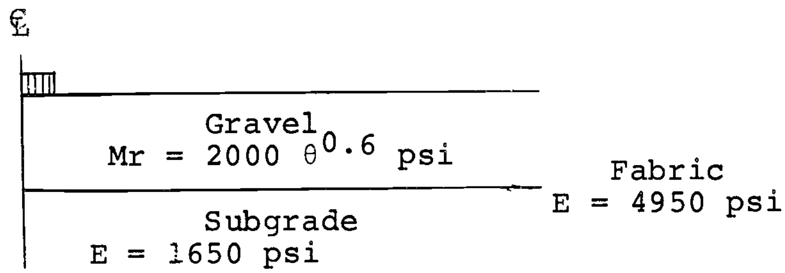
VII. IMPLICATION OF FINITE ELEMENT METHOD OF ANALYSIS AND DESIGN OF GRANULAR SURFACE ROAD WITH FABRIC LAYER

The purpose of this chapter is to investigate the possible methods of analysis of roadways with fabric and to select a suitable criteria. Considered are the layered elastic, finite element and Boussinesq theories.

7.1 Analysis by Finite Element Method and Layered Elastic Theory with Iteration

A typical test section and element configuration for the finite element method of analysis is shown in Figure 7.1. The radial distance of the side boundary is 96 inches. The depth to the bottom boundary is 150 inches. The finite element method used in this study set a limit to the resilient modulus of granular materials. The input was specified in such a way that whenever θ was less than 0.0001 psi, the modulus was calculated from θ = 0.0001 psi. This was done because it was felt that granular materials cannot resist tension and the modulus of granular materials should be very small when tension stress existed.

The layered elastic theory used the computer analysis by Kasianchuk (29). The program can handle non-linear properties of granular materials by the iteration method. First, the modulus of the granular material is assumed from the input parameter. Then the program computes the bulk



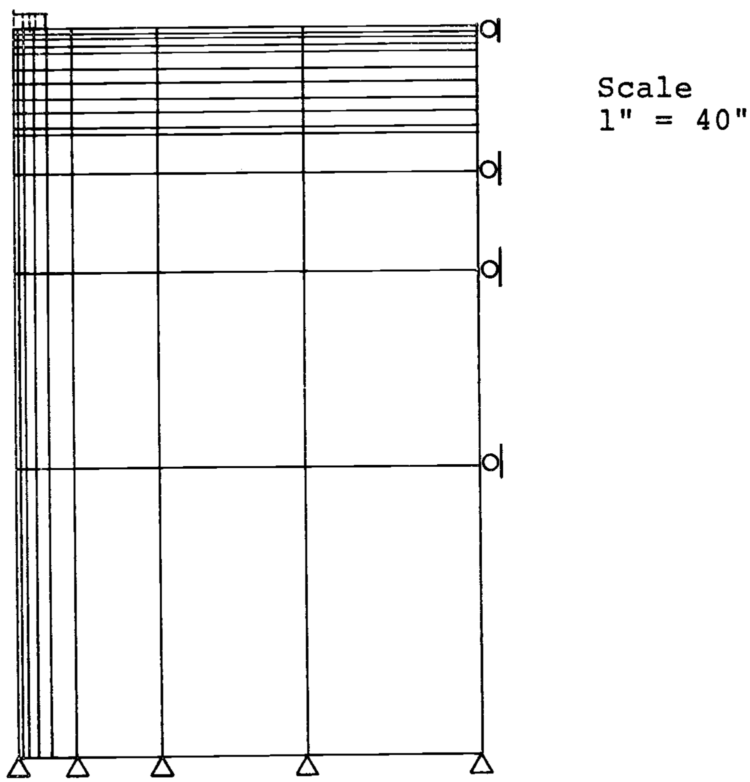


Figure 7.1. Typical test section for layered elastic analysis and mesh configuration for finite element method.

stress and substitutes it in the relation $Mr = K1\theta^{K2}$. If the assumed modulus is close to the computed modulus, the computer stops and uses the modulus to compute the stresses and strains. If not, the modulus computed will be used as an input parameter to calculate the next trial. This process is complete as soon as the trial modulus is close to the computed modulus. The computer program was specified to stop after eight iterations and use this modulus as the input parameter.

The material properties for input have been evaluated in Chapter 5. The moduli of elasticity of the granular materials used are $Mr = 1200\ \theta^{0.6}$ and $Mr = 2000\ \theta^{0.6}$ which are believed to represent the extreme values found in the test sections. The Poisson's ratio used is 0.4. The modulus of elasticity of the subgrade used is calculated from the relation that Es = 1500 CBR psi. The Poisson's ratio is 0.45. The modulus of elasticity of fabric used is assumed to be linear elastic and is taken from Figure 5.15, for the stress level that is expected in the test section. The dynamic modulus of Fibertex 400 and Mirafi 140 are 4950 and 7500 psi, respectively. The Poisson's ratio is 0.3.

7.1.1 Deflection Comparisons

Typical computed shapes of the deflected test sections are plotted in Figure 7.2. The sections selected represent

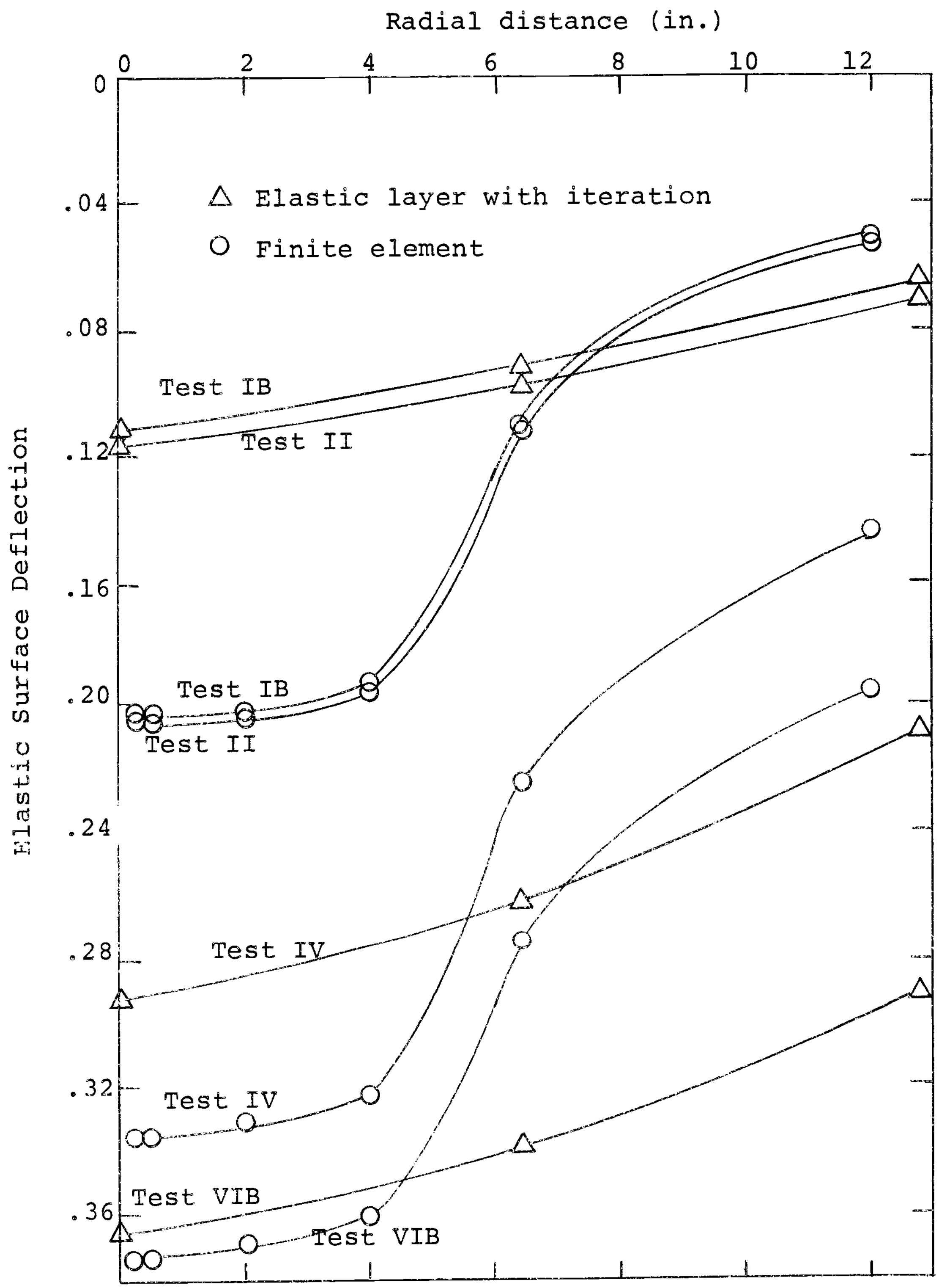


Figure 7.2. Computed surface deflections of test models.

tests I_B, II, IV, and VI_B. The modulus of the granular material over the stiffer subgrade condition is close after seven iterations, but for the softer subgrade condition the modulus is not close after eight iterations. The elastic deflection obtained from the finite element method is higher than from the layered elastic theory and the finite element predictions are closer to the measured values.

The maximum surface elastic deflections of each test section are shown in Table 6.1. The maximum surface deflections calculated from layered elastic theory and the finite element method are compared to those measured in the model tests. Figure 7.3 shows the relation between the maximum surface deflection measured and calculated by the finite element method. The straight line is the line for the measured equal to the calculated.

The resilient moduli used in the analysis are $M_R = 1200\ \theta^{0.6}$ and $M_R = 2000\ \theta^{0.6}$, representing the densities of granular materials of 104 lb/ft^3 and 115 lb/ft^3, respectively. In the test sections the density varied from 99 lb/ft^3 to 118 lb/ft^3. The densities of test sections from 99 to 110 lb/ft^3 were analyzed using $M_R = 1200\ \theta^{0.6}$ and sections with densities from 110 to 117 lb/ft^3 used $M_R = 2000\ \theta^{0.6}$. The finite element method predicted the elastic deflection close to the measured values and should be used to predict the stresses and strains of the test sections. Therefore, possible criteria that will be discussed later

Table 7.1. Comparison between computed and measured deflections.

Test No.	Measured (in)	Calculated (in)		
		Finite element		N-layer w/iteration
		$Mr = 1200\ \theta^{0.6}$	$Mr = 2000\ \theta^{0.6}$	$Mr = 2000\ \theta^{0.6}$
I.A	.110		.1483	.1184
I.B	.135		.2206	.1106
I.C	.175		.2095	.1237
II	.120		.2050	.1176
III.A	.524		.3251	.2598
III.B	.512	.3189		.2291
III.C	.375	.1849		.1357
IV	.475	.4641		.2935
V	.459	.5446		.4080
VI.A	.300	.4375		.2806
VI.B	.520	.5011		.3659
VI.C	.825	.5883		.4573
VII.A	.579	.5054		
VII.B	.86	.5972		

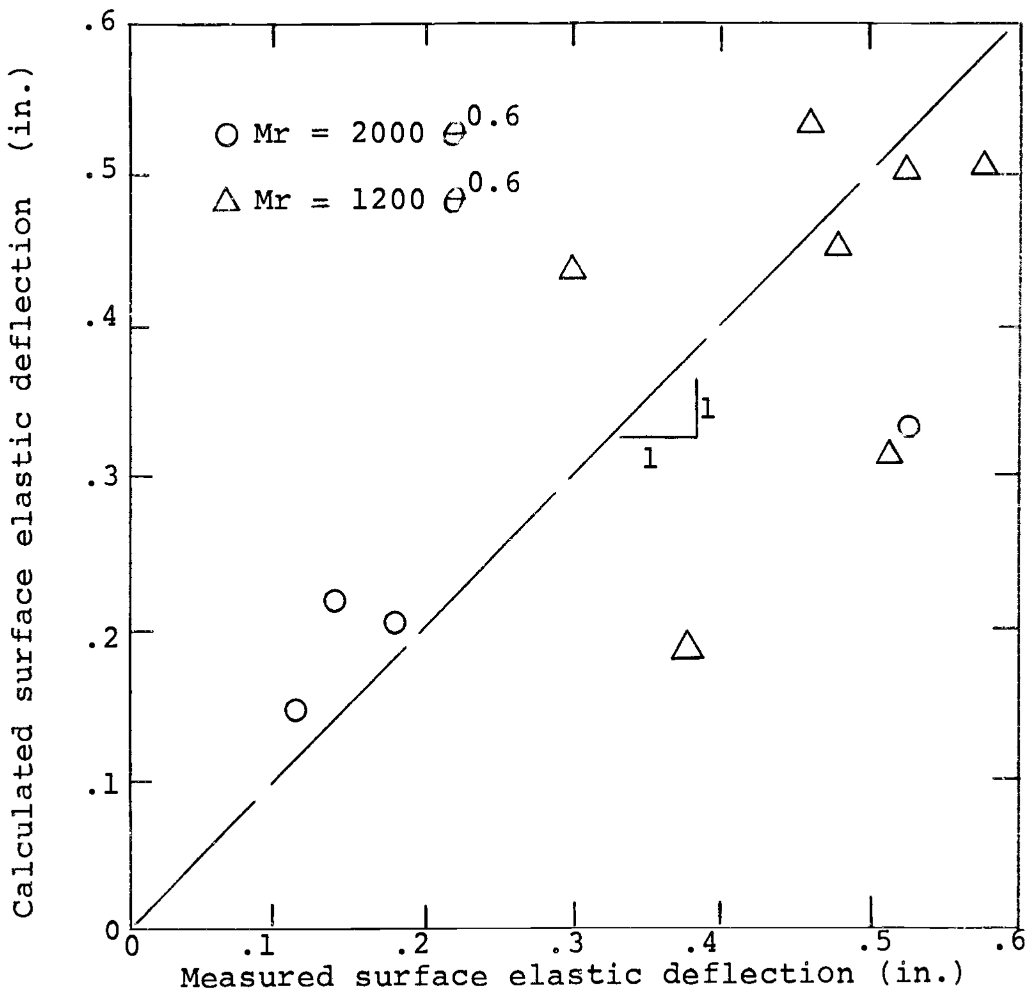


Figure 7.3. The relation between measured and calculated surface elastic deflection by finite element method.

will be based on the finite element method and the Boussinesq theory.

7.1.2 Comparison of Vertical Stresses

The vertical stresses on the center line of the load as computed by the finite element method, layered elastic theory with iteration, and the Boussinesq theory are shown in Figure 7.4. Since the Boussinesq theory considers only one layer, the vertical stress obtained by the Boussinesq theory is the same regardless of the material properties. The layered elastic theory and the finite element method calculate stresses based on the material properties of each layer. The vertical stress calculated from the finite element is between those obtained by layered elastic and the Boussinesq theories. The Boussinesq theory computes stresses close enough to those by finite element method, that it can be used for a first approximation of vertical stress in most cases.

7.2 Possible Criteria for Design

The relations between the rut depth in the subgrade and surface for each test section are shown in Figures 6.2 through 6.6. With these results and the theory of elasticity, a criteria for design can be established.

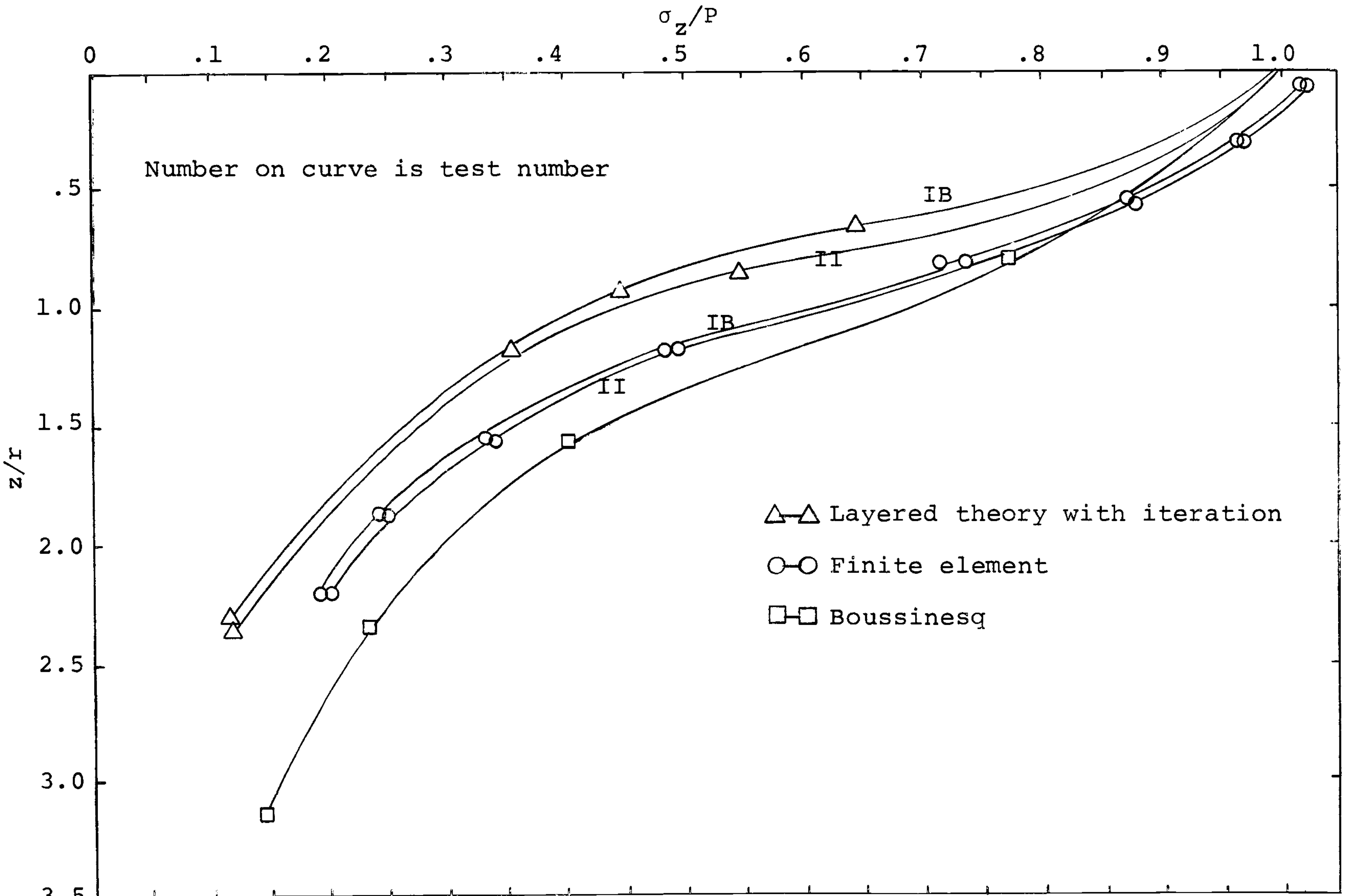


Figure 7.4. Vertical stress at center line of load.

7.2.1 Vertical Stress on Subgrade Criterion

Using the Boussinesq theory, the vertical stress on subgrade of each test section can be analyzed. The rut depth in subgrade and surface at 100 load application can be taken from Figures 6.2 through 6.6. Knowing this and the penetration resistance of the subgrade, the relations between the ratio of vertical stress on subgrade to the penetration resistance of subgrade and the rut depths at 100 load application are plotted in Figures 6.8 and 6.9. The discussion of these results is presented in Chapter 6.

Knowing the rut depth that can be accepted in the surface of the subgrade and the strength of soil, the allowable stress on the subgrade can be determined. If the load and radius of load is known, the required thickness of granular surface can be determined. This method should work very well if the fabric used is Fibretex 400 as it is the primary fabric used in this study. Furthermore, this relation can be used to indicate the effectiveness of fabric layers. This is discussed in Chapter 8.

7.2.2 Materials Failure Criteria

Each material is combined to form the roadway structure. The granular material and subgrade soil failures usually can be defined by permanent deformation. Fabric fails by rupture in tension. Fatigue may be a factor with the fabrics. It is necessary to consider the failure of each material separately as well as a system.

7.2.2.1 Subgrade Soil

The subgrade strain criterion has been shown to be a good criterion to prevent permanent deformation in flexible pavement design. The subgrade strains of the test sections are analyzed using the finite element method mentioned earlier in this chapter. The number of load applications that cause a rut of two inches in subgrade is taken from Figure 6.2. Then the relations of vertical strain on subgrade and number of load applications that will cause rut in subgrade of two inches are plotted in Figure 7.5. The relation is approximately a straight line on log-log plot.

7.2.2.2 Fabric Layer

We learn from the model tests and the laboratory tests of the fabrics that the fabric does not fail by fatigue at lower stress levels. One sample did fail by fatigue for 48 percent of the tensile strength of fabric. This implies that the fabric is likely to fail by fatigue at high stress levels. Therefore, control of the stress level in the fabric is a possible method of controlling the failure of fabric. Figure 7.6 is the maximum and minimum radial tensile stress in fabric calculated from the finite element method mentioned earlier. The maximum and minimum radial

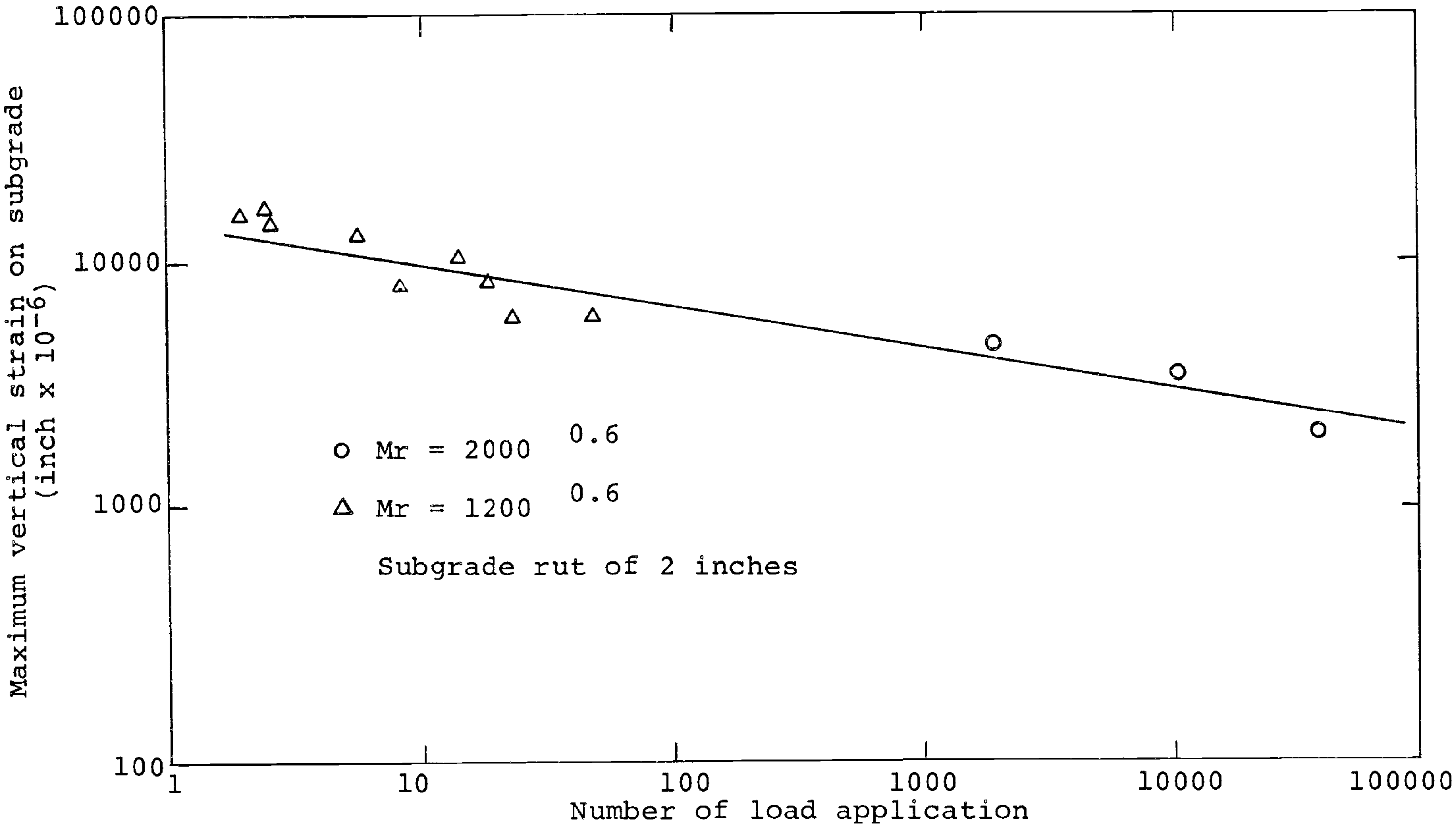


Figure 7.5 The relation between maximum vertical strain on subgrade and number of load application.

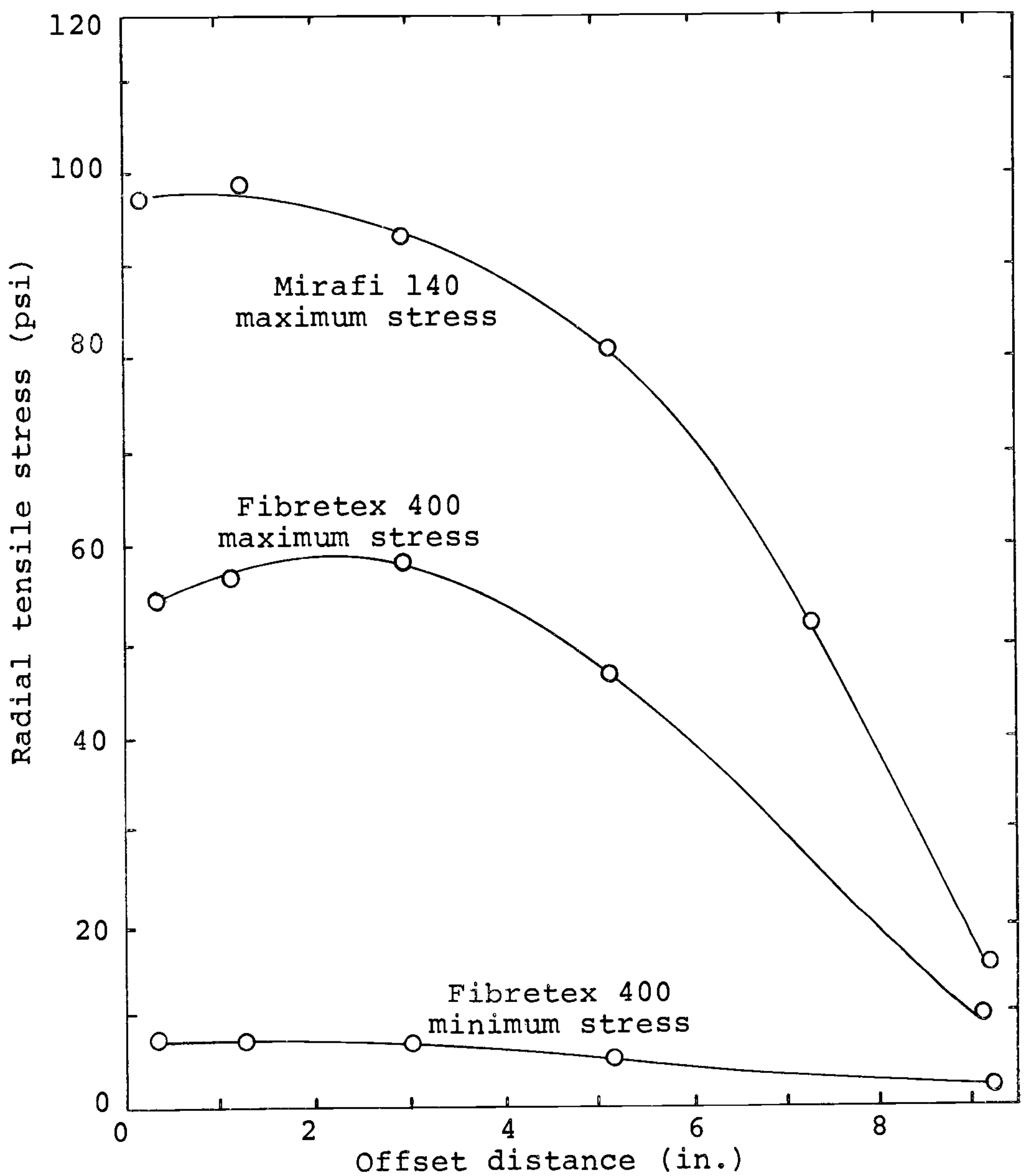


Figure 7.6 Radial tensile stress in fabric calculated by finite element method.

tensile stresses in the fabrics are plotted with the radial distance and range from 8 to 96 psi. The maximum stresses shown are approximately 1/10 of the strengths of the fabrics. The results of Test III can be used to investigate the effect of various loads on radial stresses in the fabric layer. The radial stresses in the fabric due to the loads of 3000, 5000 and 9000 pounds were 17.5, 30.5 and 36.3 psi, respectively. It is evident that the radial stress increased less than twice when the load doubled, and it tends to increase at a decreasing rate for higher loads. If the wheel load were twice as much as the 9000 pound equivalent wheel load used as standard in these tests, the radial stress in the fabric should be less than twice that calculated for a 9000 pound load and the radial tensile stresses should be less than the stress level that would cause fatigue failure in the Fibertex 400.

7.2.2.3 Granular Materials

The static failure of granular materials will occur when the shearing stress is greater than the shearing strength ($\tilde{\sigma} \geqq \sigma \tan \phi$) of the materials. Suppose ϕ is 30° then the granular material will fail when the ratio of shear stress to normal stress (τ/σ) is greater than 0.5. Brown and Pell (7) also limited the ratio of radial stress to the vertical stress to 0.5 at the bottom of the granular surface material. To test this limit, the relation between the ratio of radial stress to vertical stress at the bottom of the granular surface and the initial rut at one load application are plotted in Figure 7.7. It is shown that the initial rut increases as the ratio of radial stress to vertical stress increases.

The shearing stress at the interface between the fabric and granular surface material can also be investigated by the relation in Figure 7.7. Since the radial stress and the shearing stress are approximately equal at the bottom of the surface course, the radial stress can be used to indicate the shear stress. Note that the maximum ratio of $\sigma_r/\sigma_z(\tau/\sigma_z)$ should be limited to 0.5 or complete failure may occur in the granular surface. However, this is not the case for dynamic load. As seen in Figure 7.7, when σ_r/σ_z is greater than 0.5, no abrupt change occurs in the initial rut of the top surface. Instead, a progressive development of rutting occurs.

7.3 Summary and Conclusion

Using the finite element method with the material properties of granular materials, subgrade soil, and fabric; the calculated deflections compared closely to those measured from the test sections. The subgrade stress limit criteria using the Boussinesq method is convenient and quick to determine the conditions for which the fabric should be used. It can predict rutting at 100 load

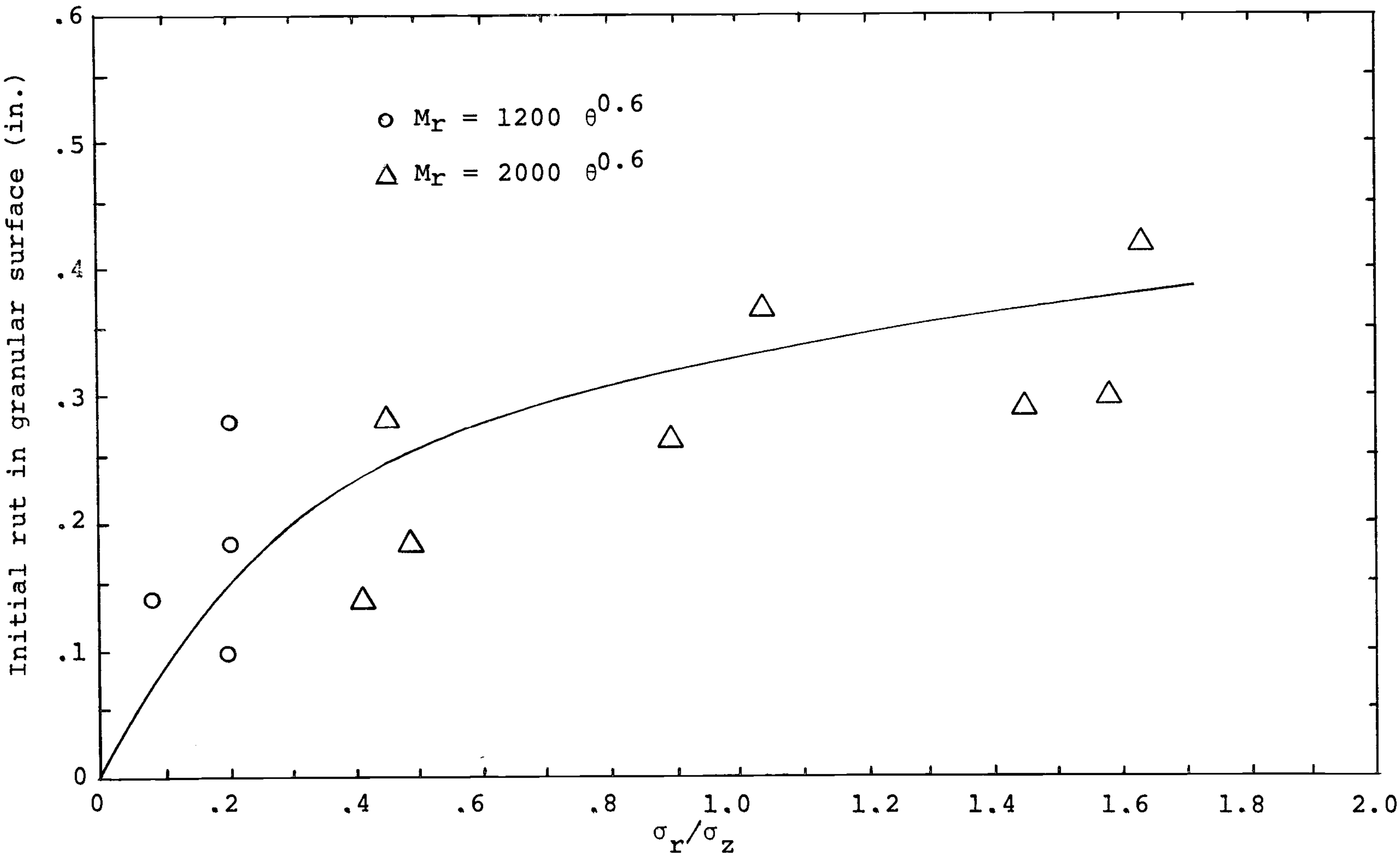


Figure 7.7 The relation between initial rut and stress ratio at bottom of granular surface.

applications in the surface and subgrade if Fibretex 400 is used. Separate criteria might better provide that the material properties are adequately accounted for when a high speed computer is available.

VIII. EVALUATION OF THE EFFECTIVENESS OF FABRIC LAYERS

This chapter will discuss the effectiveness of fabrics with respect to their reinforcing actions. The scope is limited to the information presented and developed previously.

A first approximation of a fabric's effectiveness can be made from the ratio of vertical stress on subgrade to penetration resistance of the subgrade. If the ratio is equal to about one or more, use of fabric may be effective. This is obtained from the relations in Figure 6.8.

To better define the conditions where fabrics are effective, the relationships between the thickness reduction due to Fibretex fabric and subgrade support conditions were developed and are shown in Figures 8.1 to 8.3. Three different equivalent wheel loads are compared in Figure 8.1. They include a 1000 pound wheel load representing a pickup truck, a 9000 pound maximum legal limit highway load, and a 20,000 pound wheel load of an off-highway vehicle. The maximum thickness saved is obtained from the heaviest wheel on the softest subgrade. Thickness saved decreases as the load decreases and as subgrade strength increases. Figure 8.1(b) shows the same relationship relative to the rut developed in the subgrade. The significant difference is in the thickness saved. The

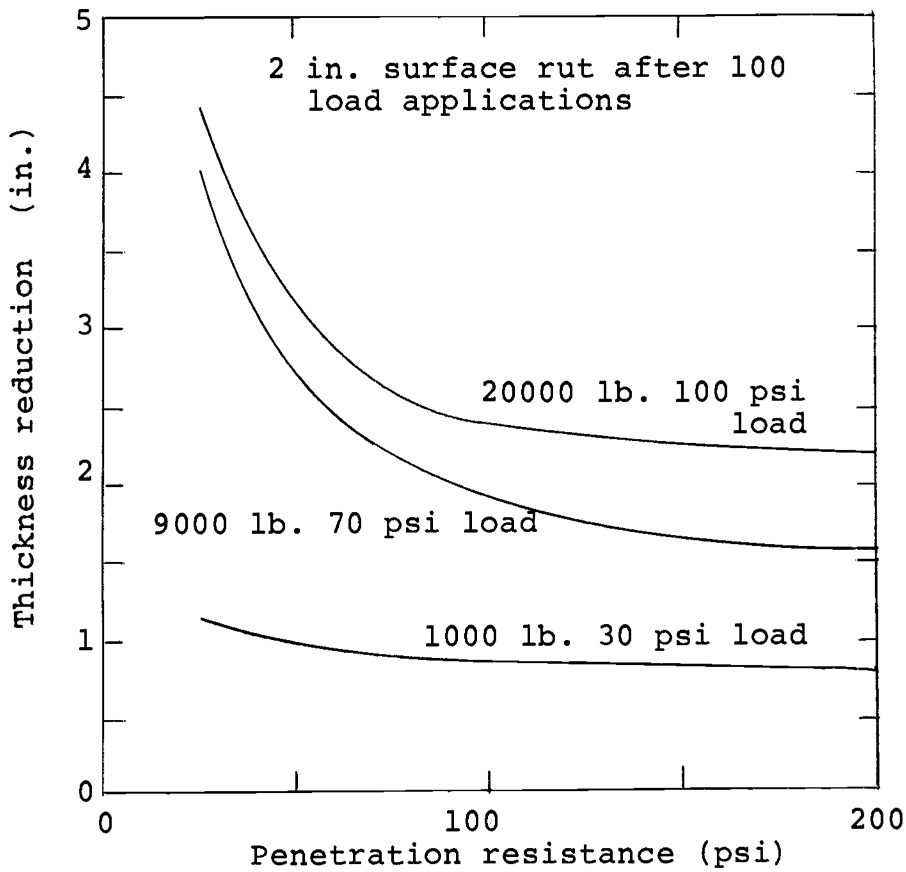


Figure 8.1(a). Thickness reduction with Fibretex fabric as a function of wheel load and surface rutting.

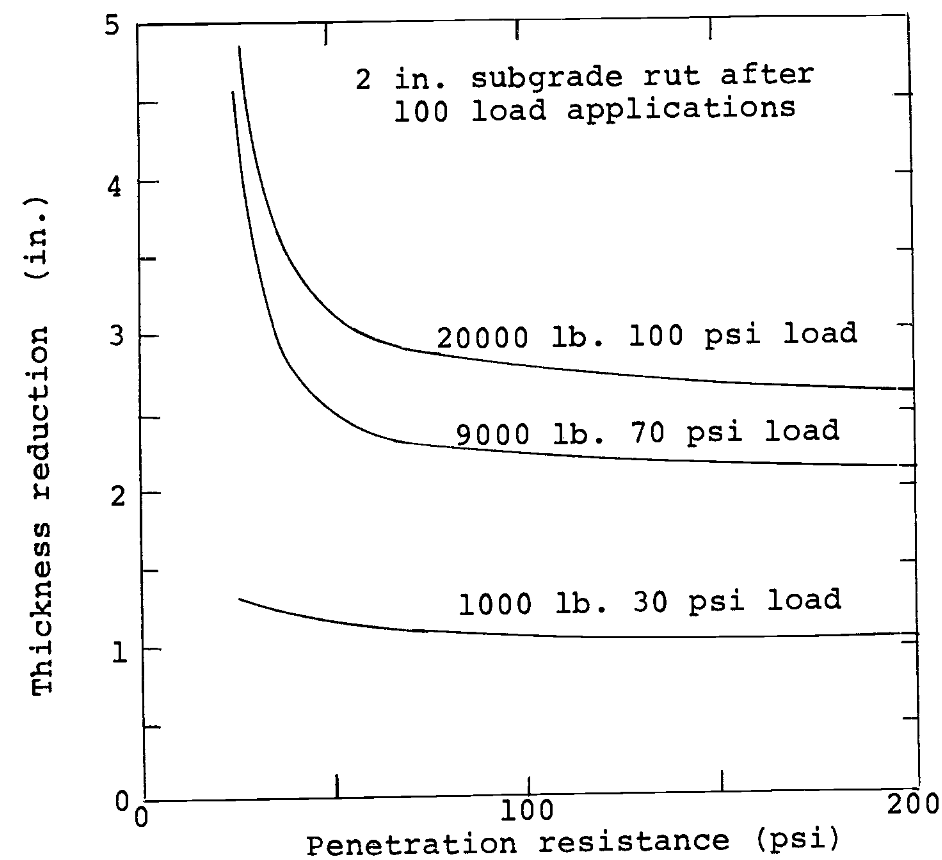


Figure 8.1(b). Thickness reduction with Fibretex fabric as a function of wheel load and subgrade rutting.

thickness reduction relative to the subgrade rut is considerably smaller. This may be explained by the poor granular base used in the tests. If the properties of the granular surface are better, the rate of rutting in the surface will be smaller; the total rate of rutting will shift toward that of the subgrade line and the thickness saved relative to surface rutting will be smaller. Figures 8.2 and 8.3 show that the thickness reduction with the use of fabric is relatively independent of the allowable rut depth and of the number of load applications.

The results indicate that fabrics may be effective when deep ruts can be tolerated and for very soft subgrades. This suggests that fabrics are likely to be suitable in two cases: (a) to use as a stabilizing platform for construction equipment on soft ground, and (b) to use as a stabilizing layer for granular surfaced roads for heavy wheel loads on very soft subgrades.

When the fabric is used as reinforcement, for a construction roadway, the allowable surface rut can be deep and the required thickness of granular surface can be determined from the relation between the ratio of vertical stress on subgrade to penetration resistance and the surface rut depth.

When the fabric is used in a permanent road, the rut in the subgrade whould be limited to about two inches for the life of the roadway structure. To analyze for the

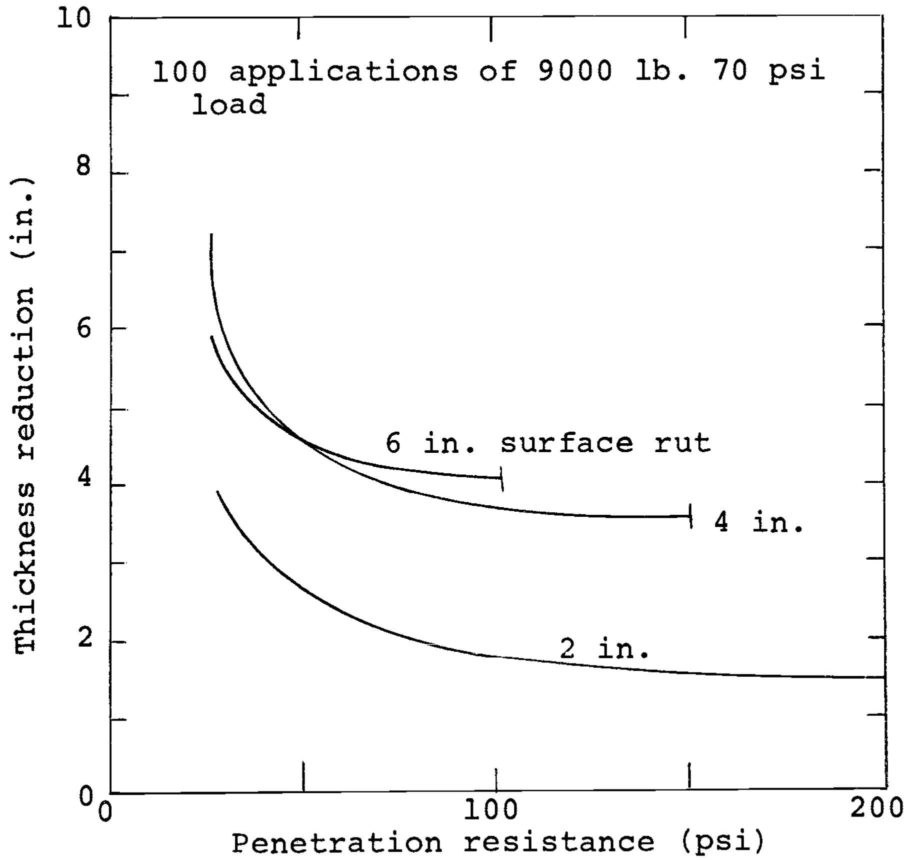


Figure 8.2(a). Thickness reduction with Fibretex fabric as a function of surface rut depth.

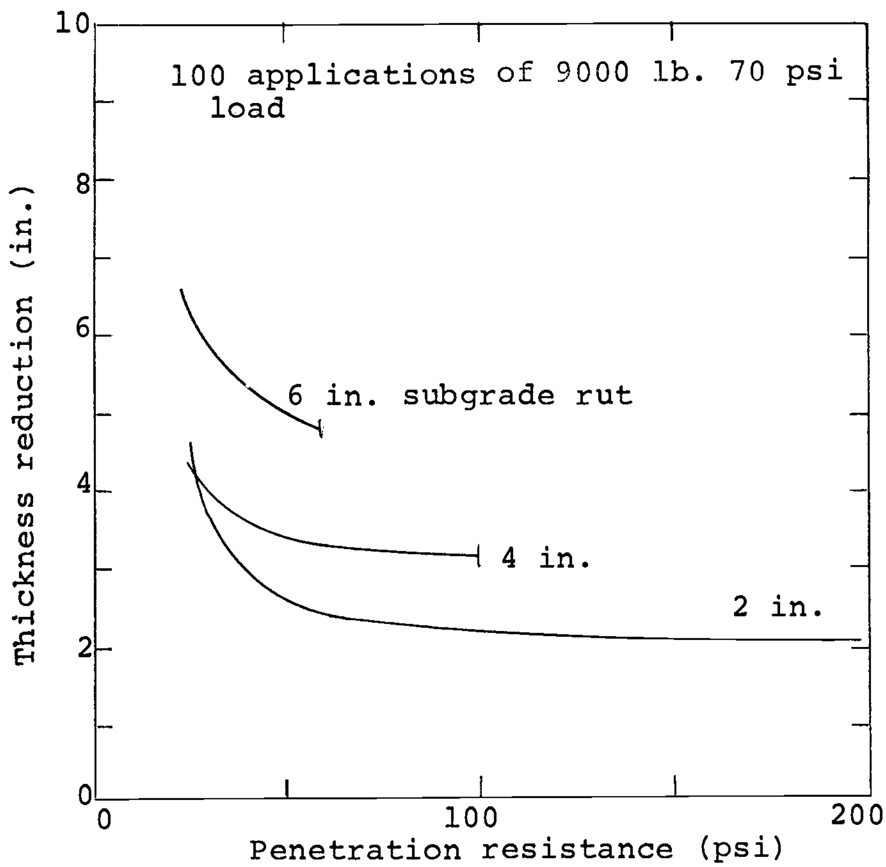


Figure 8.2(b). Thickness reduction with Fibretex fabric as a function of subgrade depth.

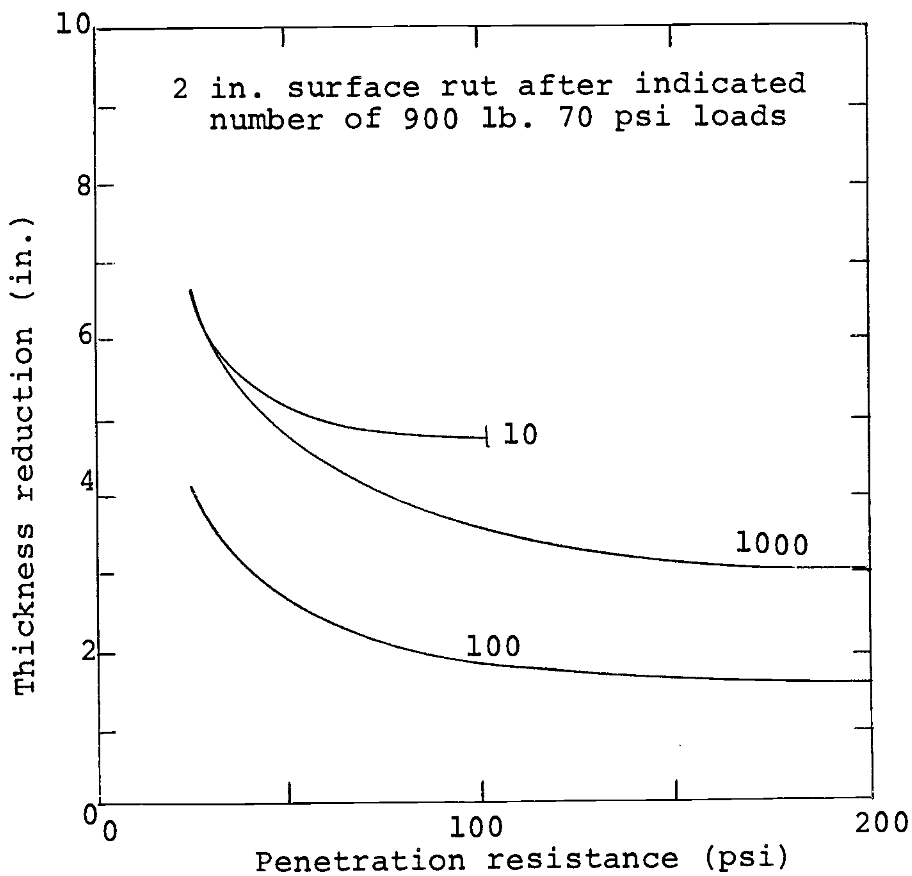


Figure 8.3(a). Thickness reduction with Fibretex fabric as a function of number of load applications and surface rutting.

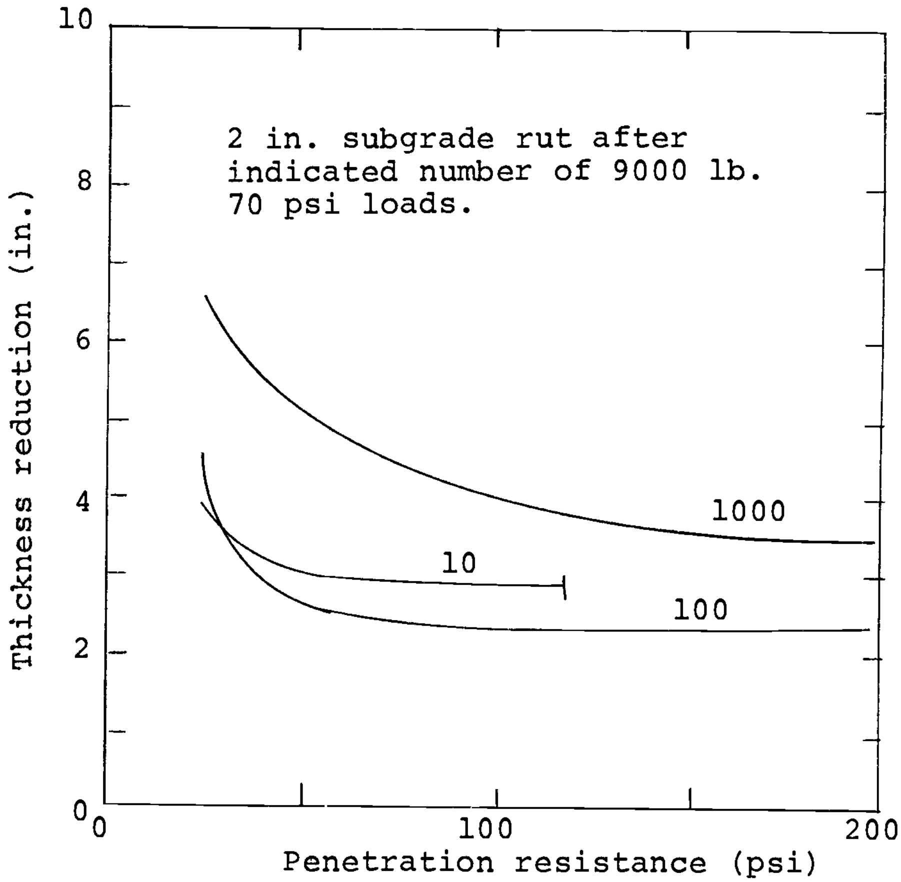


Figure 8.3(b). Thickness reduction with Fibretex fabric as a function of number of load applications and subgrade rutting.

thickness required, a first approximation may be made by the method indicated above. To analyze more accurately, the finite element method could be used. After the thickness is estimated and the dynamic properties of all materials evaluated, the finite element method is used to calculate the maximum vertical strain at the top of the subgrade, maximum radial stress in the fabric and the ratio of radial stress at the bottom of base to the vertical stress at that point. The number of load applications and the criteria for fabric and base material can be checked from the relations in Chapter VII. If the values are not satisfied, another granular layer must be tried. This method offers a solution for the fabric radial stress which is one of the major criteria that the Boussinesq theory cannot analyze.

IX. CONCLUSIONS

The following conclusions are drawn from this study:

1. For the fabric to act as a reinforcing layer, it must be between two materials which are less stiff than the fabric.
2. The effectiveness of the fabric decreases as the properties of the base improves. The fabric is not effective in reinforcing a paved roadway.
3. Fabrics may effectively be used to stabilize temporary construction roads on soft soils and to stabilize granular surfaced roads for heavy wheel loads on subgrades with a CBR value of less than one.
4. Fatigue failure of the fabric should be checked.
5. Cone penetrometer, proctor penetrometer, or field vane tests can be used to evaluate soft subgrade properties and predict rut depth when Fibretex fabric is used.
6. The finite element method computes deflections corresponding to measured values when proper materials properties are used.

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APPENDICES

APPENDIX A

Results of Parametric Study of Roadway with Reinforced Layer

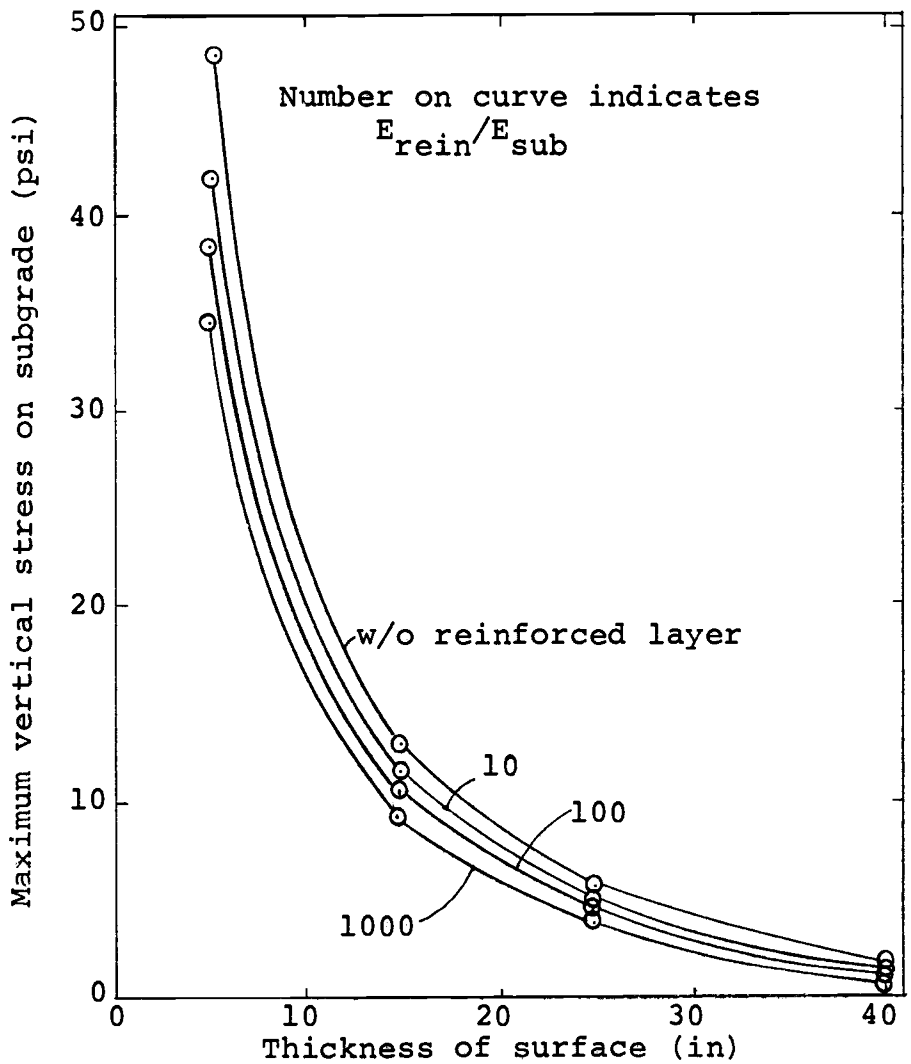


Figure A.1(a). The relation between maximum vertical stress on subgrade and thickness of the surface with and without reinforced layer for $E_{surf}/E_{subgrade} = 2$.

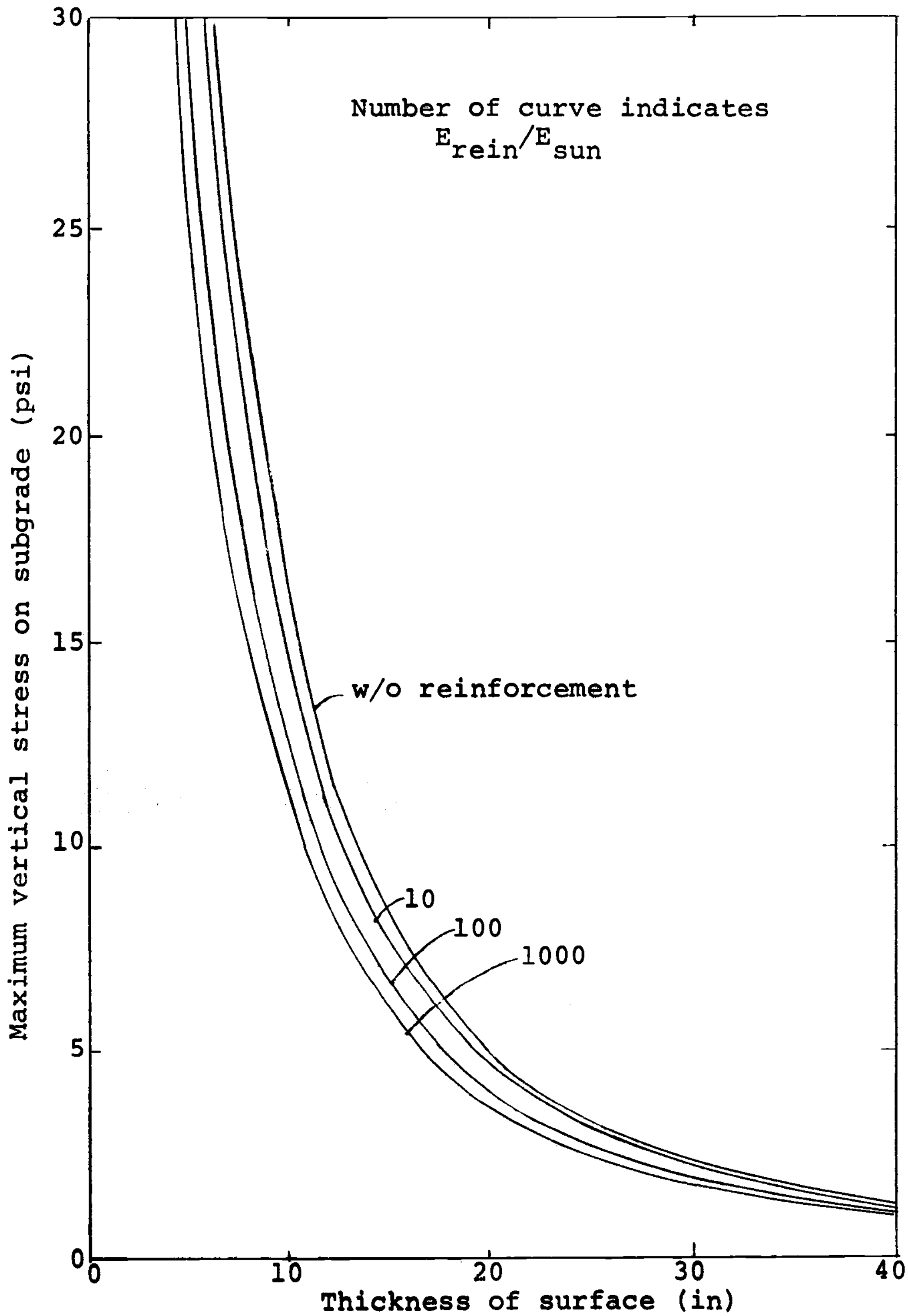


Figure A.1(b). The relation between maximum vertical stress on subgrade and thickness of surface for $E_{surf}/E_{subgrade} = 5$.

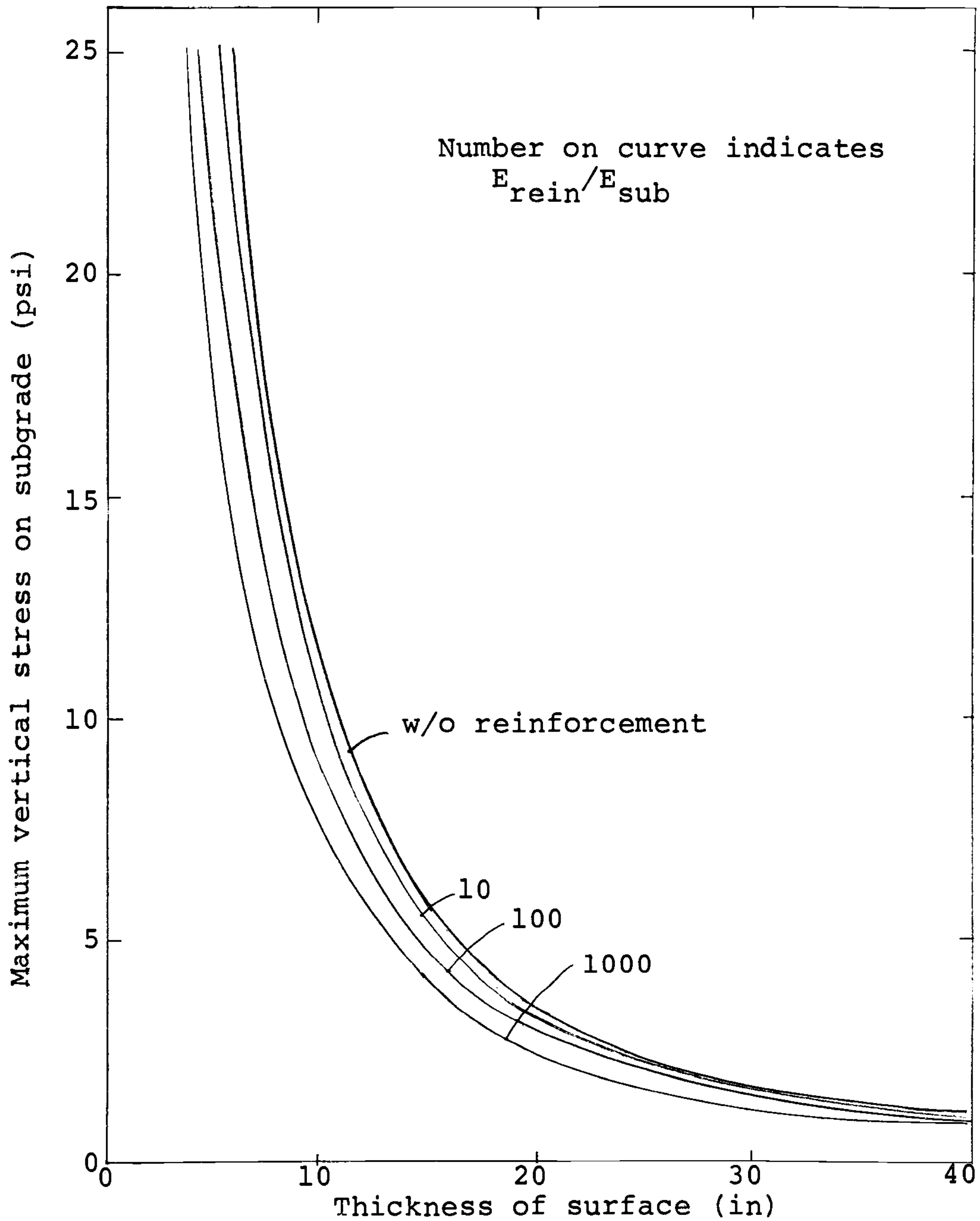


Figure A.1(c). The relation between maximum vertical stress on subgrade and thickness of surface for $E_{surf}/E_{subgrade} = 10$.

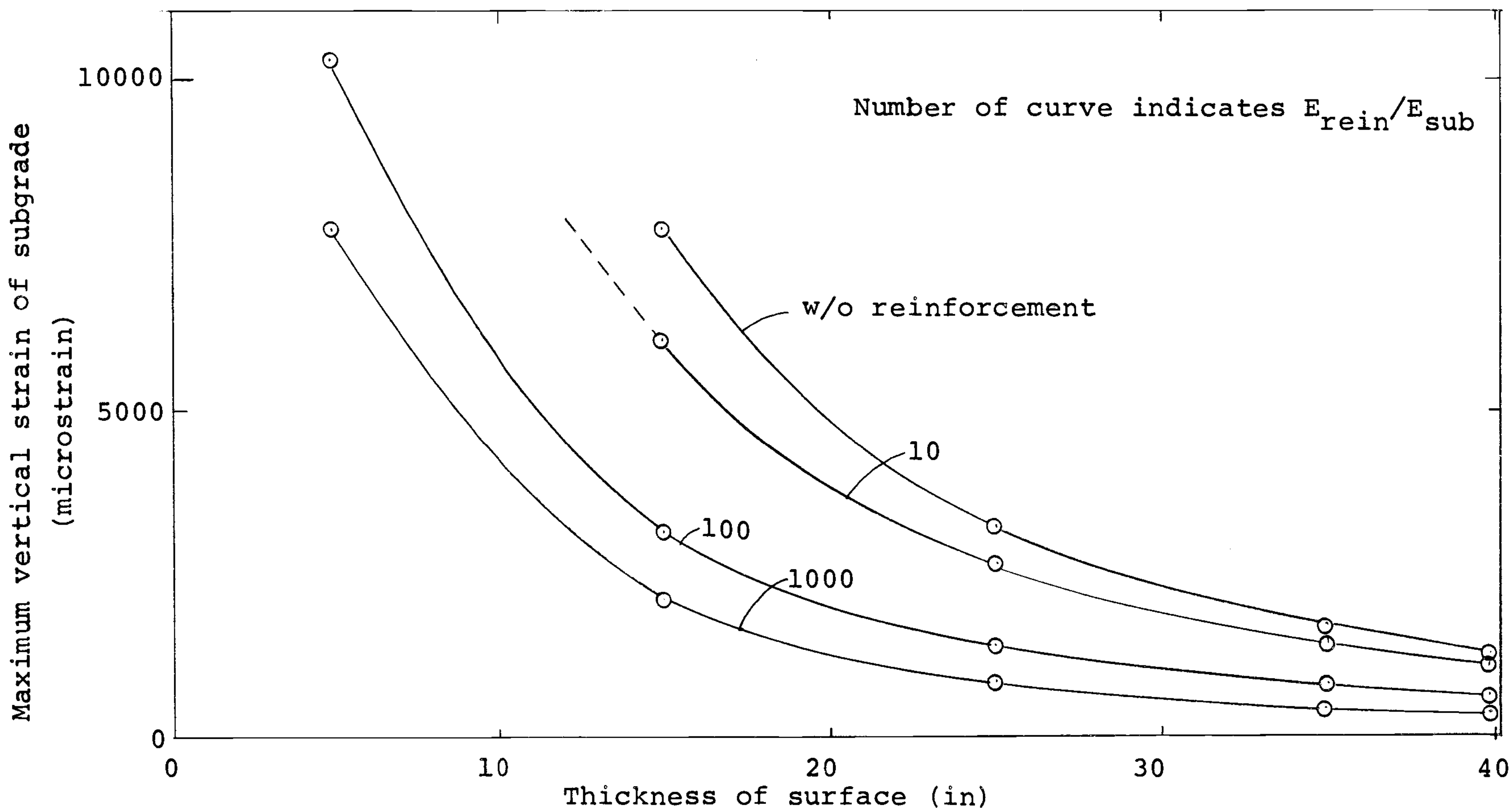


Figure A.2(a). The relation between maximum vertical strain of subgrade and thickness of surface for $E_{surf}/E_{subgrade} = 2$.

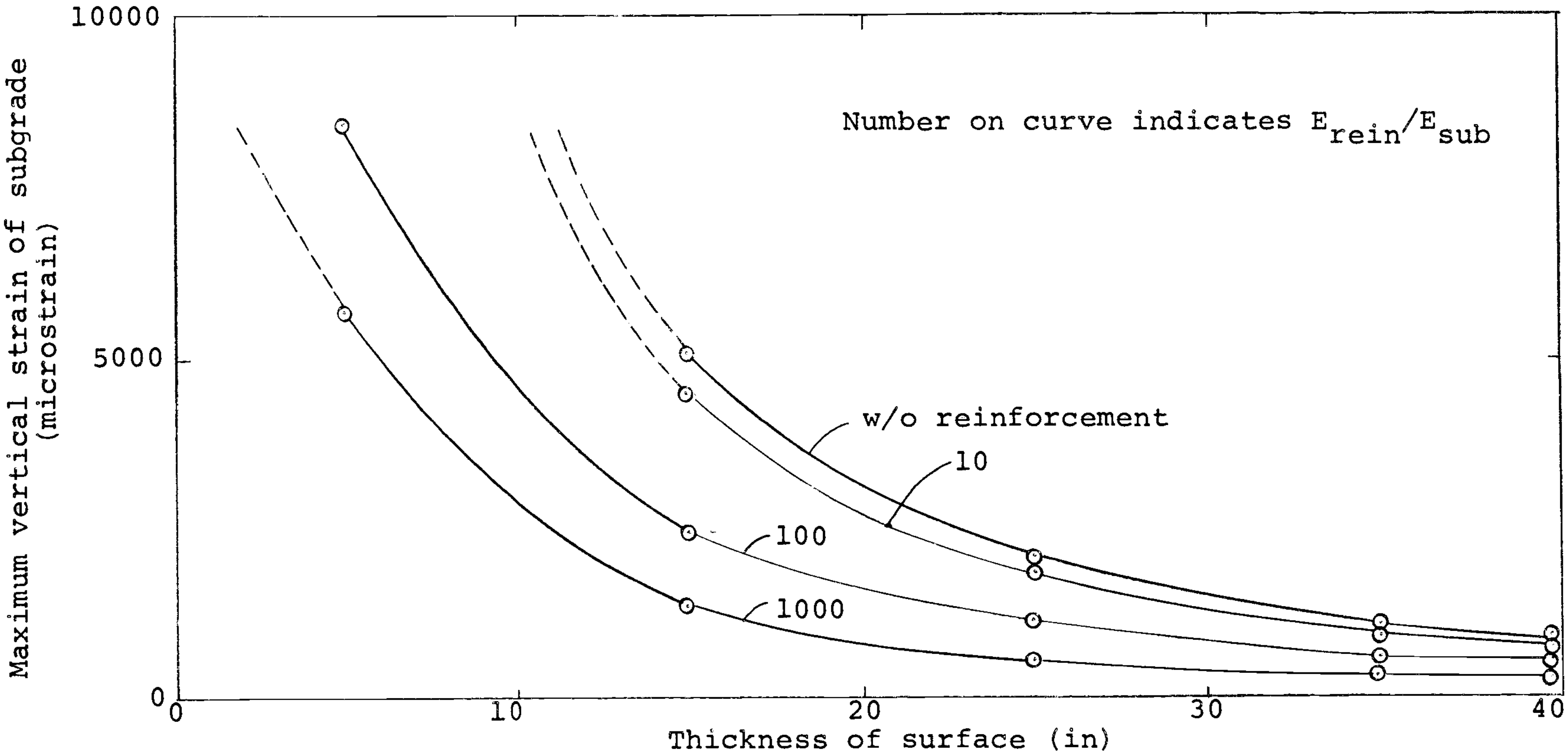


Figure A.2(b). The relation between maximum vertical strain of subgrade and thickness of surface for $E_{surf}/E_{subgrade} = 5$.

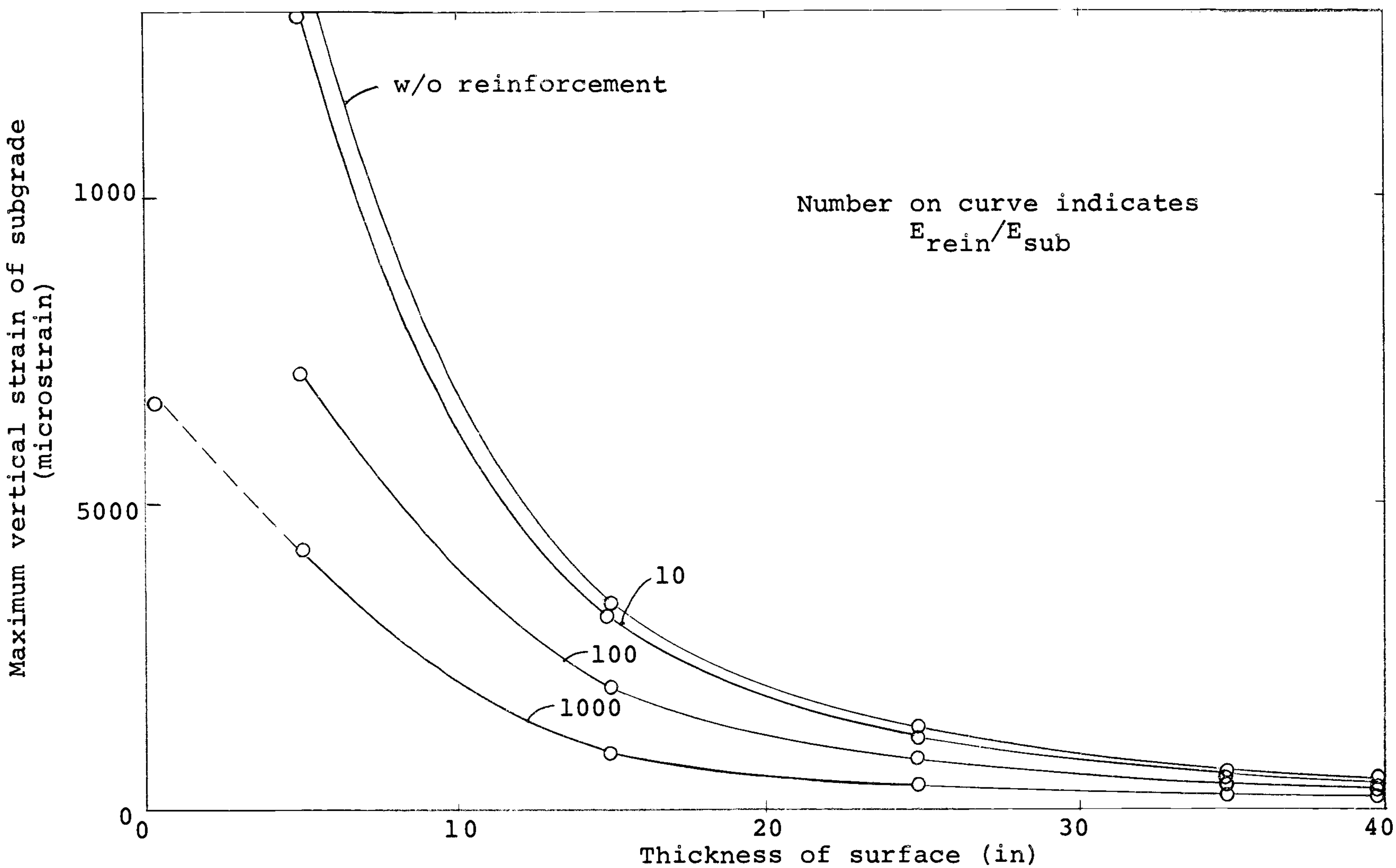


Figure A.2(c). The relation between maximum vertical strain of subgrade and thickness of surface for $E_{surf.}/E_{subgrade} = 10$.

APPENDIX B

The Effects of the Test Tank Boundaries

The effects of the test tank boundaries were analyzed using the SAP IV finite element program (7). The mesh configurations of the systems assumed to represent test and field conditions are shown in Figures B.1 and B.2. The model used is axisymmetrical. Very stiff springs are used to represent the side of the tank and the bottom of the tank is considered fixed. To simulate the field conditions, rollers are used to prevent horizontal movement but allow vertical movement. The bottom of the subgrade is also considered to be fixed. The analysis shows that the tank boundary reduces the surface deflection about 30 percent.

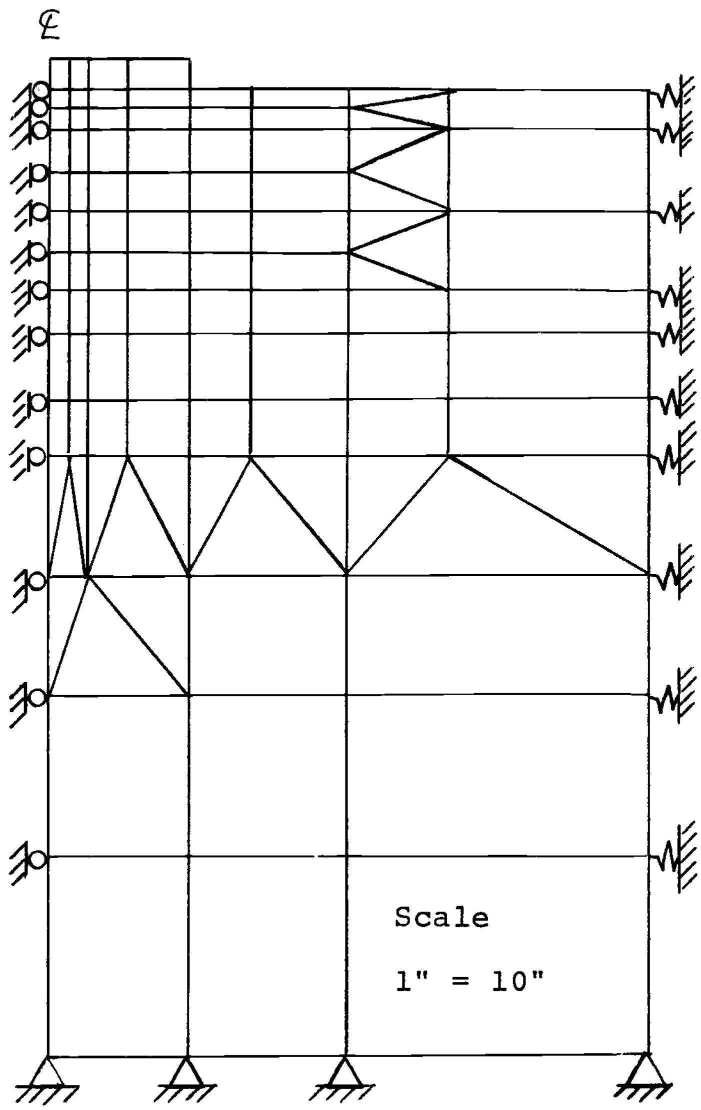
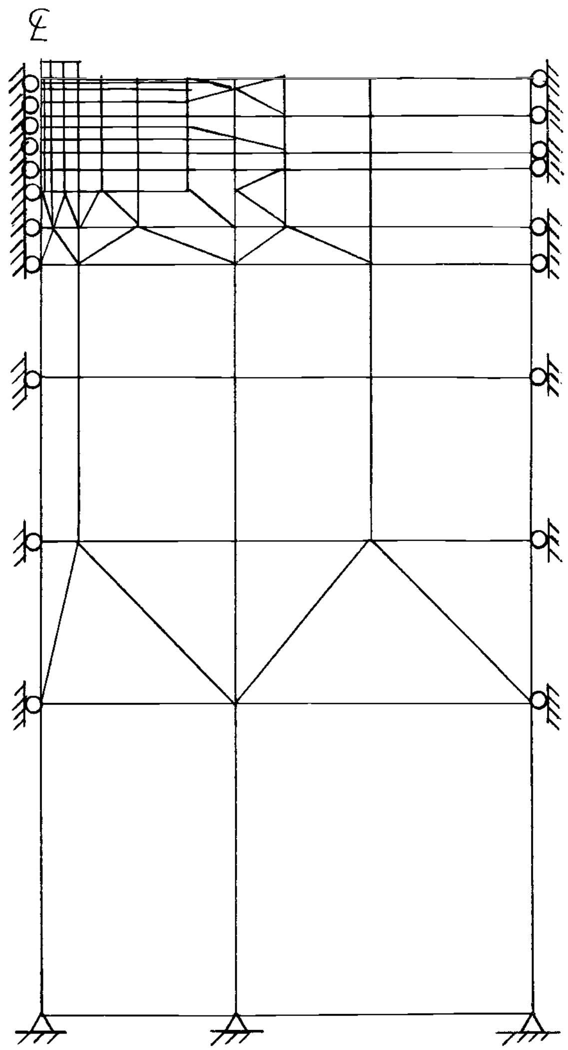


Figure B.1. Mesh configuration assumed to represent test tank conditions.



Scale: 1" = 30"

Figure B.2. Mesh configuration assumed to represent field conditions.