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16. Abstract

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EXECUTIVE SUMMARY REPORT

# SUBGRADE ELASTIC MODULUS FOR ARIZONA PAVEMENTS

by

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&

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Submitted to

Arizona Department of Transportation

Highways Division

for

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ABSTRACT

Elastic modulus of subgrade is an important input parameter in the newly developed rational methods for the design of pavements. In order to provide guidance for the selection of realistic values of $E_s$ for pavement design in Arizona, testing was performed at five field sites typical of Arizona subgrades. Testing involved plate bearing tests, refraction seismic, CBR, Dynaflect, and Road Rater. Correlations are made and guidelines are presented for incorporation of the findings into a pavement management system.

# "SUBGRADE ELASTIC MODULUS FOR ARIZONA PAVEMENTS"

Executive Summary

Robert W. Crossley, P.E.
George H. Beckwith, P.E.

## Introduction

Continually rising costs coupled with an increasing scarcity of quality roadbuilding materials in many parts of the world in recent years have created an increased incentive for engineers to optimize the design of concrete and asphaltic pavements. As is the case today in many areas of engineering technology, empirical methods for pavement design, founded on what had been considered "successful" past designs, are giving way to mechanistic procedures utilizing fundamental material properties.

In a typical mechanistic flexible pavement design procedure based on elastic theory, a three layer system consisting of an asphaltic concrete or bituminous bound layer, an unbound granular base layer, and an infinite subgrade is described. A two layered system modeling full thickness asphaltic concrete designs can also be analyzed by most procedures. Response of each of the materials is a function of the two fundamental elastic parameters, modulus of elasticity (E) and Poisson's ratio ($\nu$), which must be assigned to each layer. Other important input parameters include the traffic data (the number of wheel loads, size, and tire pressure), and thicknesses of the various layers. With these, the performance of selected pavement sections can be modeled.

This research effort focused on a single input parameter, the elastic modulus of the subgrade as it applies to mechanistic design procedures. The research was intended to develop specific procedures to determine elastic moduli to represent subgrade response as it affects typical pavement sections in Arizona and the Southwest.

## Summary of Research Effort

While investigation of the elastic properties of all types of soils was an overall objective of this effort, a more specific goal was to critically examine the load response of typical Arizona soils for which little information is available in the published literature. For this reason, major emphasis was focused on field testing cemented desert clayey sands, sandy clays, and clay-sand-gravel mixtures, and on other partially saturated or desiccated cohesive soils. Little data is available in the literature on these types of soils which are difficult to evaluate in the laboratory.

The research effort was divided into five general headings. These are the literature review, sensitivity analysis, field testing, data correlation, and recommended evaluation procedures.

## Literature Review - Concept And Use of Elastic Parameters in Soils Engineering And Pavement Design

In recent years it has become common to find published procedures for analyzing problems of foundation behavior and soil-structure interaction employing models based on elastic theory. To be used effectively, these methods require the integration of two contrasting disciplines; the precise and methodical theory of elasticity and the empirical and interpretative discipline of soil mechanics.

Historically, elastic theories were used primarily to describe the behavior of a material whose properties were homogeneous and isotropic, that is, a material which today would be called a "continuum". With the advent of high-speed computers containing large storage capacities, it has been possible to extend elastic analyses to provide solutions to the response of media which are layered or contain other complex geometries.

In contrast, the theories of soil behavior and the art of "soils engineering" have been developed, for the most part, by practitioners during this century and are based heavily on empirical evidence. Early efforts of modern soil mechanics focus largely on soft, saturated clays with the time dependent nature of deformations being reflected by theory of consolidation. Until recently, soil has been treated as a "particulate" material reflecting the observation that it is composed of discrete grains or particles.

For the past several years, practitioners of soils and rock engineering, as well as transportation engineers involved with pavement thickness designs, have witnessed the introduction of numerous analyses which treat earth materials as though they behave elastically. Methods for calculating the settlement of footings, piles, and embankments, as well as the dynamic response of machine foundations, are examples where elastic theory provides solutions which are sufficiently accurate for practical design.

In the area of pavement design, there always has been a need for some form of stiffness factor for bearing capacity evaluation of the subgrade. Newer pavement design methods which use the computer (such as the CHEVRON and BISTRO Programs) are nearly always based on multilayer elastic theories, as are some of the more simplified longhand methods. Obviously, the results are only as meaningful as the values of E (modulus of elasticity) and $\nu$ (Poisson's ratio) for subsurface materials, which are chosen as design inputs. Unfortunately, too often, "handbook" values, based on simple correlations with index soil properties, are the basis for these inputs.

Values of E modulus of soils may be determined in the laboratory from tests using samples of finite dimensions (in either an "undisturbed" or remolded condition) or may be measured in-situ. Common laboratory methods include uniaxial compression tests, unconfined compression tests, resonant column tests, and dynamic triaxial testing. Many agencies have developed or accepted correlations between E modulus and California Bearing Ratio, R-value, and soil classification and behavioral index parameters. In-situ tests which have been used to determine E modulus include plate bearing tests, seismic refraction, CBR, steady-state vibration techniques, and the Menard pressuremeter.

Mechanistic flexible pavement design methods have been developed and published by many agencies throughout the developed world. Approximately 20 of these were reviewed in conjunction with this study, including several methods presented at the 1977 Fourth International Conference - Structural Design of Asphalt Pavements (1)* held in Ann Arbor, Michigan. Primary purpose of the review was to focus upon the means by which developers of current pavement design methods have chosen to characterize the response of subgrades.

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*Numbers in parentheses correspond to references listed at end of report.

It was found that there is a parallel between the overall degree of sophistication incorporated in a given method and its procedure to model the subgrade. For instance, in VESYS IIM (2), which is the most intricate of the pavement design systems, a nonlinear elasto-plastic subgrade model is called for. For most methods, purely elastic models of subgrade response are preferred. The rheology of soils is too imprecise to justify the effort of determining creep and permanent deformation indices. Of the approximately 20 methods reviewed, five recommend dynamic triaxial testing to determine $M_R$ for the subgrade. These are in the form $M_R = A\,\sigma_d{}^B$ or $M_R = A\,\theta^B$. It should be noted that this is also a common way to test and characterize the response of bituminous bound materials and asphaltic concrete.

Another 10 methods suggest that users adopt simple correlations, most often, the Heukelom and Foster (3) relationship E = 1500 x CBR. Only four of the methods rely strongly on in-situ testing, while most endorse laboratory tests as being suitable and probably more economical.

In most agencies, worldwide, pavement designers prefer that subgrade samples be tested in ways that simulate the poorest possible environmental condition, namely, saturation of the subgrade. Accordingly, pavements are often designed and built as if subgrade support was minimal.

## Sensitivity Analysis

In any design procedure, one of the engineer's responsibilities is to decide how to allocate finite fiscal resources to obtain values for his input variables. Obviously, it makes little sense to spend thousands of dollars per mile seeking an exact value of a parameter which has negligible effect upon the thickness of the final pavement. With respect to subgrade modulus, a sensitivity analysis was used to put economic factors in proper perspective.

Using the Chevron Research Company method (4) and the Kentucky Department of Transportation method (5), charts were prepared which plotted thickness of pavement section required for various traffic loads as a function of subgrade modulus. These are given as Figures 19 through 22.

From the four figures in this review, certain conclusions can be derived.

1. As subgrade modulus increases, the life of a pavement increases for a given highway section.

2. For a given subgrade modulus, the life of a pavement increases logarithmically with section thickness.

3. The importance of subgrade modulus in any design method is most keenly felt in the range of E = 5000 to 25,000 psi (which is the range of most Arizona subgrades). As an example, using Figure 22, a pavement 4 inches thick over an 8 inch base and a subgrade whose subgrade modulus is 10,000 psi has a 20-year ADT life of about 7. This same section with a subgrade modulus of 20,000 psi has an ADT of 50 and with E = 30,000 psi, ADT = 150. Similarly, for a full thickness pavement of 6 inches over a 10,000 psi subgrade, 20-year ADT is 8 while for E = 20,000 psi, ADT = 48.

Therefore, the evidence seems to indicate that in using mechanistic flexible pavement design methods, the economic benefits to be derived from applying a thoughtful and physically reliable value of $E_s$ justify a reasonable effort in obtaining such values.

## Field Testing Program

The purpose of this field testing program was to gather and analyze a substantial amount of information from sites which are typical of Arizona subgrades, but which at the same time are unlike the classical soil types which have been the object of many prior investigations.

Field testing was undertaken in two phases. In Phase I (fall, 1976) three sites were examined, with emphasis placed on precision in quantifying subgrade response. At the two Phase II test sites, (spring and summer, 1977), the emphasis was shifted to collecting large amounts of data within limited areas to investigate various factors including the degree of lateral variation in response for typical Arizona soils.

The sites were as follows:

I-10 Buckeye: Tests were performed on both a cut and fill segment of the graded and drained structure. This site is a geologically recent alluvial fan which has become moderately lime cemented.

The value of the I-10 Buckeye site lies in the fact that it is most typical of Basin and Range terrain. The degree of cementation is in the middle range of conditions insofar as induration and strength properties are concerned.

Lake Pleasant Site: This segment of graded and drained roadway traverses a pediment surface of a type which is common along mountain fronts in the Southwest. This is a gently inclined erosional surface veneered with a foot or so of fluvial gravel and residual soil. Rock, which is within a foot or so of the surface can be described as a fanglomerate; that is, a heterogeneous mixture of the transported rock fragments which have been so strongly cemented by calcium carbonate that the material is in fact lithified.

Cienega Creek Site: This site is typical of many in the central mountains of Arizona. The elevation is approximately 5000 feet and annual rainfall is more than twice that which falls on the desert. Soils at this site are predominantly residual, but the upper few feet may also contain clays derived from weathered volcanic ash deposits. Classification test data indicates that they possess a moderately expansive potential.

Rainbow Valley Site: This test site is located on an isolated piece of ranch property on a young, alluvial fan. The soil type is a silty sand with some gravel. In the topmost foot of native material, the lime cementation is predominantly weak, but below this, the cementation is moderate to strong in most places. The site proved to be extremely valuable from the standpoint of acquisition of response data of uncompacted native soil.

McCormick Ranch Site: The site provided a unique opportunity to perform testing on a controlled engineered fill of material that is similar to many subgrades in the basins of southern and western Arizona. At the same time, a nearby site consisting of the same material in native condition was available for comparison testing.

McCormick Ranch, in north Scottsdale, is geologically much younger than the other test sites, and is typical of reworked basin alluvium which is widely distributed in the Phoenix metropolitan area. The soil type is a borderline silty clay - clayey silt. Near the surface of the native (desert) site, very little cementation has developed.

The fill, which was the site of most of our tests, was placed in 1972 to a depth of about 3 feet. Compaction was to 95 percent of Standard Proctor (AASHTO 99 or ASTM D698). There has been no activity on this site during the 5 years following the placement of the fill.

At each of the five test sites, exploratory drilling and sampling, soil classification tests and dry density and moisture content determinations were initiated in order to characterize the subgrade environment in terms of commonly used parameters. In Phase I of the field testing, elastic modulus was determined using four field techniques; namely, repetitive plate bearing tests, surface refraction seismic, Dynaflect and Road Rater. In Phase II, four techniques were also employed, repetitive and nonrepetitive plate bearing tests, refraction seismic, in-situ CBR and Dynaflect.

A summary of specifications regarding performance of the various tests is given below.

Standard Penetration Testing - ASTM D1586
Classification Tests - ASTM D423 and D424
In-Situ Density - ASTM D1556

Plate Bearing Tests - ASTM D1196 (nonrepetitive) and ASTM D1195 (six cycle repetitive)

Refraction Seismic - Shear and compression wave velocities determined using the "horizontal traction method".

California Bearing Ratio - Army Corps of Engineers Method

Dynaflect and Road Rater - Deflection basin analysis techniques (internally developed).

## Results of Testing

Table 16 presents a summary of subgrade elastic modulus values determined by in-situ testing. A summary of advantages and disadvantages of the various methods is given in Table 18.

The following conclusions resulted from the testing.

- The 30 inch plate under a loading of 30 to 50 psi should be used as the reference modulus for design of highway pavements for most Arizona conditions. Smaller plates, such as the 12 inch, have been found to be too greatly affected by the local zones of stiffness, and are, therefore, not indicative of the mass response for many Arizona subgrades.

- Correlations of $E_s$ with in-situ density were poor to nonexistant. Likewise, correlations with standard penetration number were unreliable.

- Seismically determined modulus values must be reduced by a factor dependent on the strain level and dry density in order to arrive at an $E_s$ suitable for design.

- Subgrade modulus is approximately equal to 500 times the in-situ CBR.

The results of field testing at the five sites were very revealing but not entirely conclusive. At the root of the problem is the realization that no test, no matter how sophisticated or carefully performed, precisely duplicates the loading situation to which a pavement subgrade will be subjected over its design life. A second obstacle which is almost as great is the wide spatial variation in the response of subgrades over very short distances.

It is concluded that the plate bearing test should remain the primary reference for the measurement of subgrade response, and that correlative substitutes are available (in order of usefulness) in the field CBR, refraction seismic and Dynaflect. It is further concluded that in Arizona, the reference modulus of a subgrade ($E_s$) should apply to the subgrade in a condition of low moisture, to which reductions made necessary by moisture increase may be applied.

## Criteria for Selection of Subgrade Modulus For Use in Pavement Design Systems

In selecting design values of subgrade modulus, four points should be realized.

- Soil and subgrades do not behave elastically except at low level strains; nevertheless, a properly derived secant E modulus provides an adequate representation of the subgrade compressibility under highway type loadings.

- For most conditions, the most definitive field measurement of subgrade response is obtained with the 30 inch diameter plate bearing test at a stress level of about 30 to 50 pounds per square inch. This is the range of vertical stress which will be involved in the upper portion of the subgrade for most pavement designs in Arizona.

- Field (in-place) testing is considered to be much more representative of subgrade compressibility than laboratory testing due to the influence of cementation and desiccation in Arizona soils. Tests other than plate bearing may be employed, but an adjustment of some kind must usually be made to the modulus value, in order to obtain a value of $E_s$ which is equivalent to that which would be determined by the plate bearing test.

- Two or possibly three adjustments must be made to the value of $E_s$ pertaining to the 30 inch plate test in order to achieve a meaningful value of $E_3$, the modulus of the third layer, for use in a layered pavement design method.

The three adjustments are: (1) A factor to bring a measured modulus value into the range of $E_s$. The determination of this factor is dependent upon the test method. This first reduction eliminates the problems of geometry of loaded area and stress level. If large diameter plate bearing tests are performed, no adjustment is needed (other than a statistical one, to arrive at a mean or median value for a design section). (2) An adjustment to $E_s$ to account for the dynamic and repetitive nature of pavement loadings. This is a reduction factor which should not fall lower than 0.80 for compacted subgrades. (3) An Environmental Reduction Factor, herein designated ERF. This factor is to be based on an educated judgment of the expected environmental deterioration of modulus during the service life of the pavement.

In reality, the ERF is an index of the susceptibility of a subgrade to significant and permanent increase in postconstruction moisture content. This factor is as important as any in the pavement design system, as the results of the saturated plate bearing tests show that the ERF could be as low as 0.1.

The experience of pavement engineers through the world has been that moisture contents in subgrades generally increase with time. This is not necessarily the case for arid and semi-arid regions, however, as indicated by field studies in Australia (6), South Africa (7) and Israel (8).

At the 1965 Symposium on Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas (9), a panel of experts agreed that where climate is arid throughout most of the year, and where normal care is taken to remove the surface waters from roadways, via camber of the roads and necessary drainage systems, the accumulation of water beneath road and airfield pavements is prevented. In such circumstances, the soil moisture suction under sealed pavements is controlled by the mean atmospheric humidity and the moisture condition of the subgrade will differ little from that of uncovered soil.

During the past 15 years, the authors have had the opportunity to investigate subsurface conditions at numerous sites, including several operating airports in the Southwest. At Kingman, Yuma and Litchfield Park airfields, sections of pavements built during World War II were found after 20 to 25 years to have experienced only small and localized increases in moisture in the subgrade.

At the Grant County Airport (near Silver City, New Mexico), an investigation 5 and 10 years after two stages of construction revealed low subgrade moisture (very near optimum) in a lime cemented sandy clay subgrade. Annual rainfall is approximately 15 inches. It should be noted that this airfield was built with asphaltic concrete placed directly over a low permeability compacted sandy clay. It appears that this type of construction has been successful in preventing significant moisture infiltration and movement in the subgrade.

The most successful techniques for preventing moisture increases in subgrades are: (1) the placement of a full depth asphaltic concrete layer directly on dense compacted subgrade of low permeability, (2) the use of catalytically blown asphalt in a thin layer between the subgrade and subbase, (3) the use of membrane encapsulated soil layers (MESL) using a plastic sheeting or one of the newer high strength fabrics and, (4) the use of a rubberized asphalt membrane or surface seal.

All of the above techniques have been successfully demonstrated on test sections in Arizona or elsewhere in the Southwest.

Returning to the problem of assigning an EFR, the engineer must consider both the likelihood of moisture change, which is generally a function of external circumstances, along with the probable consequences of that moisture change concerning the subgrade response. The latter is a function of the internal makeup of the subgrade. Factors which should be considered in all cases include:

annual rainfall*
mean annual temperature*
slope
anticipated traffic
drainage conditions
thickness and makeup of pavement layers
use of membrane seals or other moisture protection measures

*both functions of elevation in Arizona

The Environmental Reduction Factor ERF, like the design value for traffic 20 years in the future, requires intuitive judgment and a great degree of sophistication should not be expected. Values of ERF should probably consist of only one significant figure (e.g., 0.8, 0.7, etc.).

A flow chart detailing a pavement design sequence using concepts presented in this report is shown in Figure 77.

## Summary and Conclusions

Major conclusions and recommendations are as follows:

- Major savings in costs can often be effected by employing elastic methods of pavement design analysis in Arizona conditions and determining $E_s$ by in-situ methods.

- In general, laboratory testing of Arizona soils is not the most effective means of evaluating response of pavement subgrades during their service lives.

- Various laboratory tests designed to measure soil stiffness, including cyclic triaxial shear tests, are not believed to be an effective means of evaluating subgrade stiffness for most Arizona soils. After subgrade construction, the soils typically dry below compaction moisture contents. The complex internal stresses created by this desiccation are unlikely to be duplicated in the laboratory.

- As a part of the design procedure, prior to the use of test data in analysis, it is recommended that the values of Young's modulus be adjusted to consider the level of strain, environmental effects and the effects of repeated dynamic loads by the procedures presented herein.

- Seasonal variations in moisture and temperature affect subgrade response in Arizona to a substantially lesser degree than in many other areas. Environmental effects are usually much less significant than naturally occurring spatial variations in cementation and stress fields.

- Owing to calcareous cementation and the internal stresses due to desiccation, the elastic modulus of Arizona subgrades is usually substantially higher than the "handbook" values widely published in pavement design literature. The use of these "handbook" values usually leads to conservative designs in most areas of the state.

- For most areas of Arizona, the technology exists to maintain subgrades at or below the compaction water contents (or at low natural moisture contents), enabling the use of correspondingly higher subgrade moduli in design.

It is emphasized that the methods presented herein were developed specifically for Arizona conditions. Those evaluating the methods for use in other areas are cautioned to very carefully assess the similarity of the soil and climatic conditions they are dealing with to those covered by this study.

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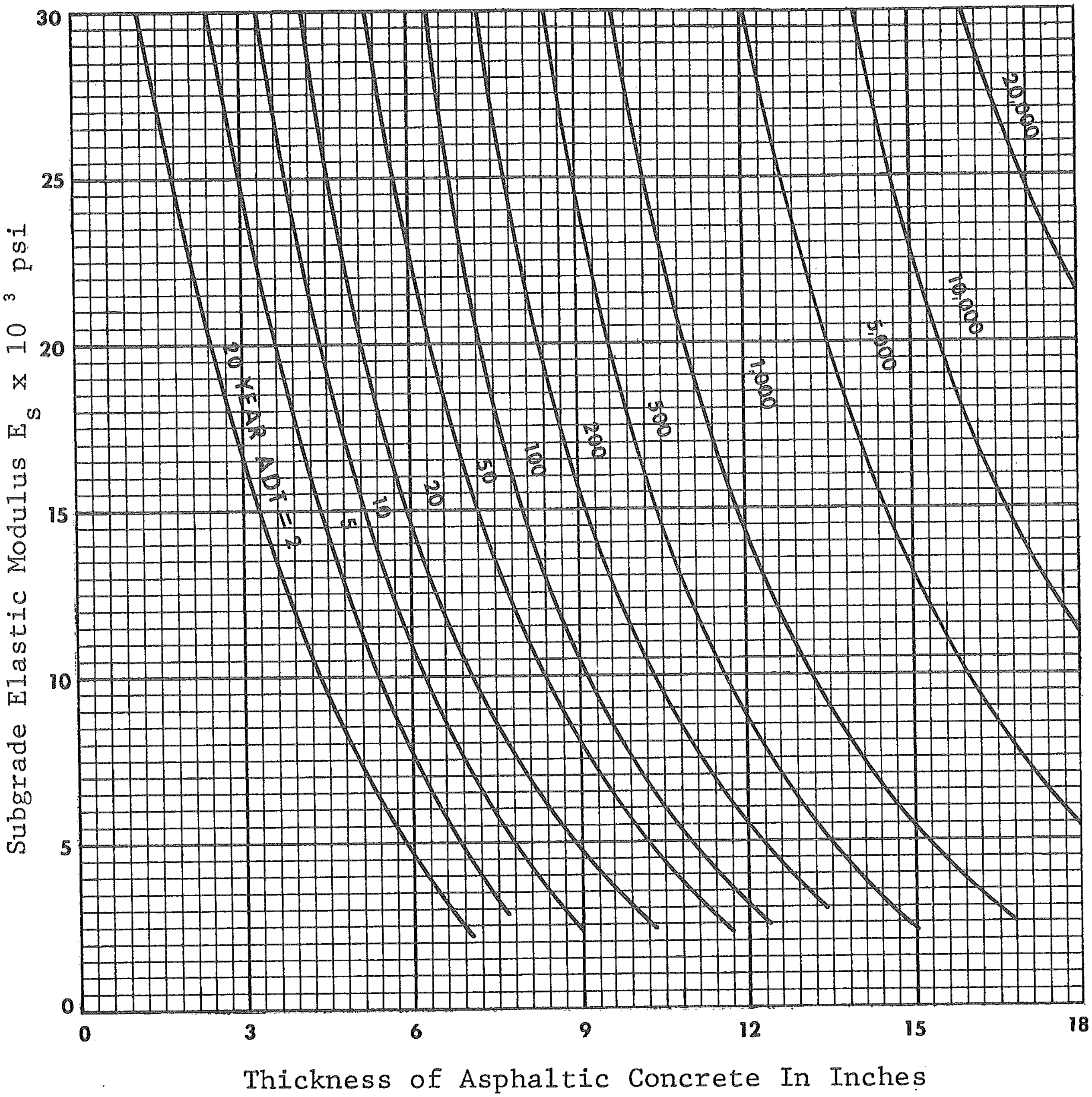



Figure 19. Design chart showing role of subgrade elastic modulus ($E_s$) in design of full thickness asphaltic concrete pavements using Chevron Research Method.

Failure the result of excessive compressive strain at the top of the subgrade (rutting).

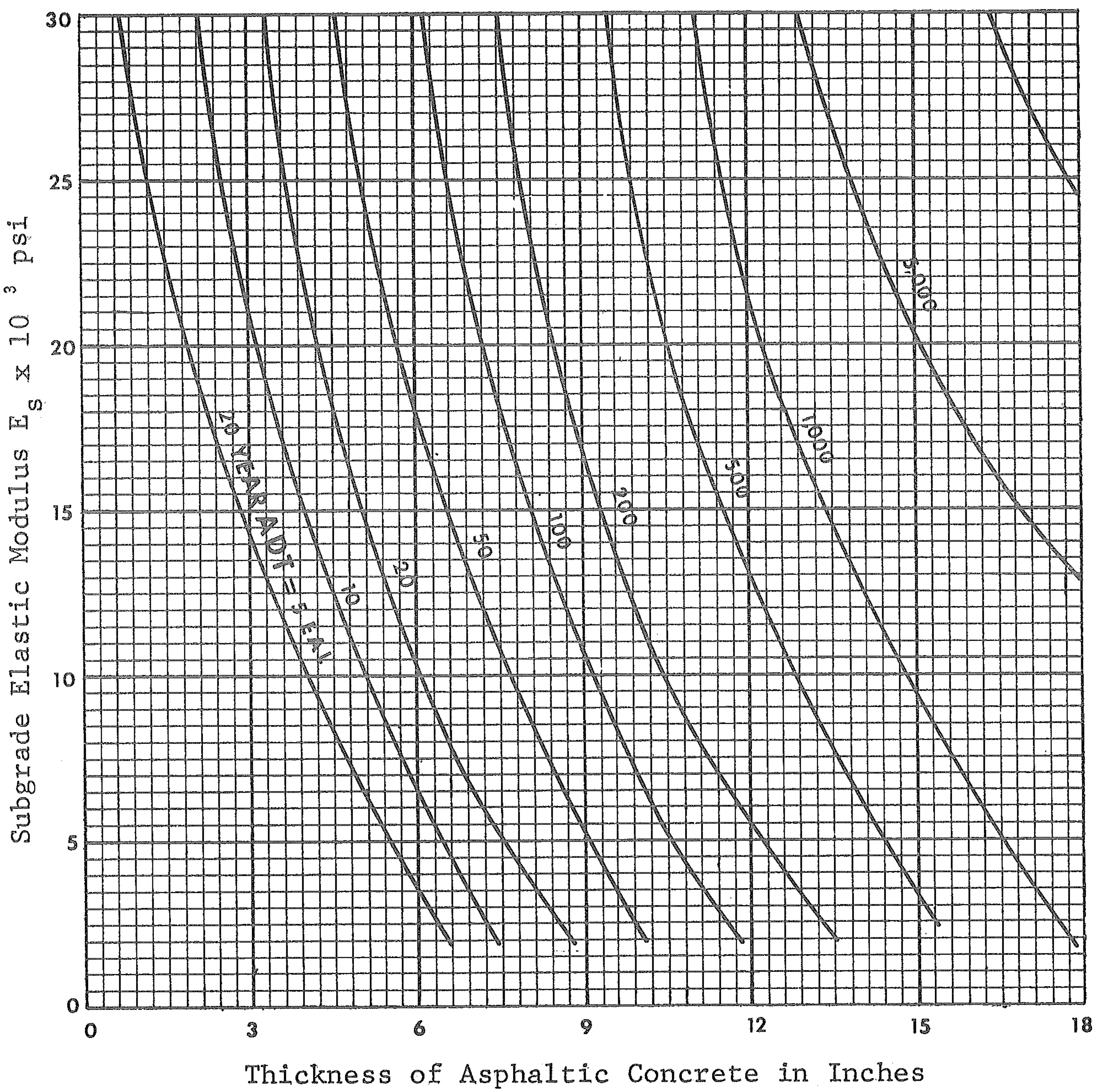
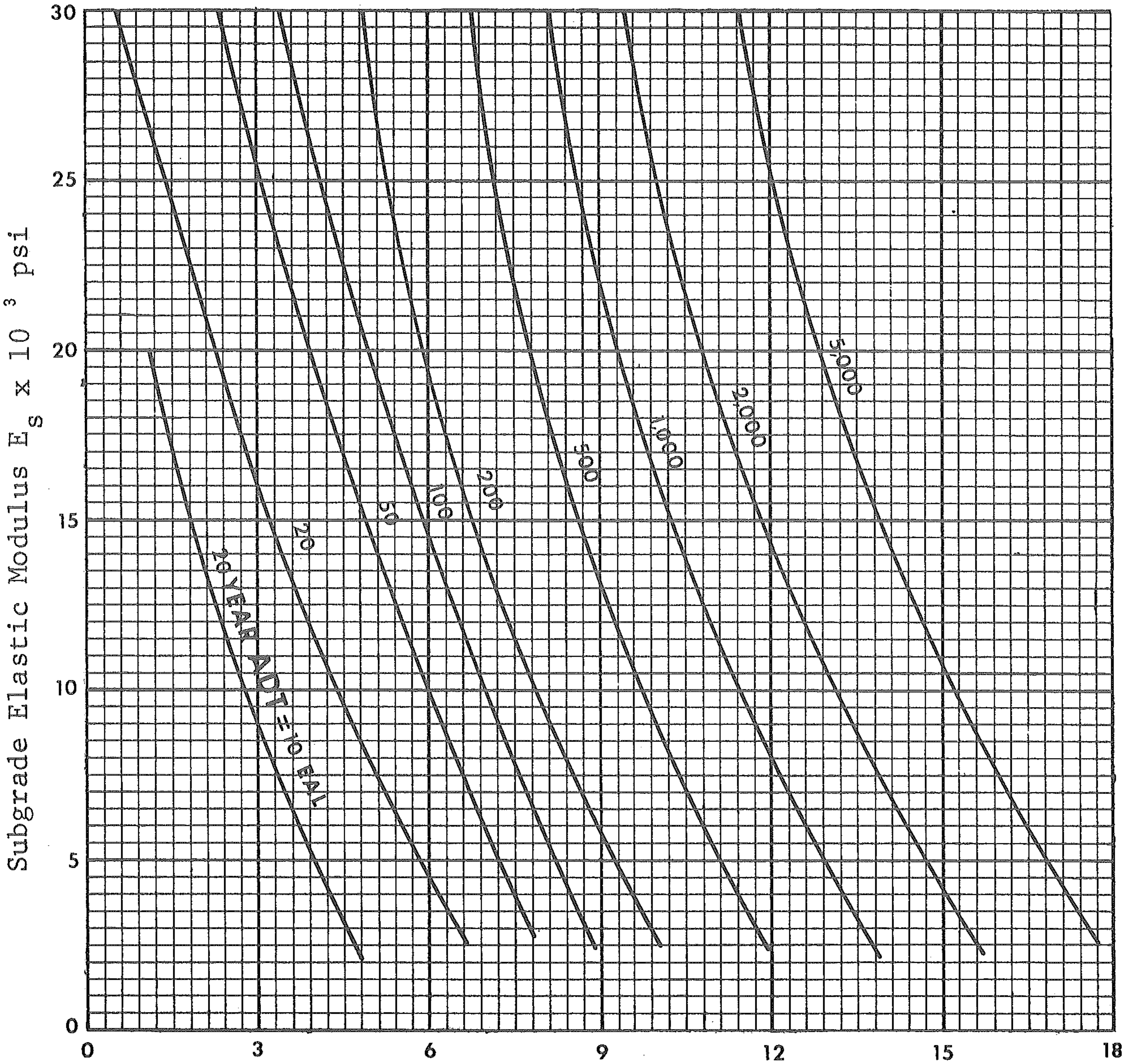



Figure 20. Design chart showing role of subgrade elastic modulus ($E_s$) in design of full thickness asphaltic concrete pavements using Chevron Research Method.

Failure the result of excessive tensile strain at bottom of asphaltic concrete layer (fatigue).

$V_v = 5\%$ $V_b = 11\%$ $E_1 = 200{,}000$ psi

$V_v$ = Volume of air voids
$V_b$ = Volume of asphalt residue




Thickness of Asphaltic Concrete in Inches

Figure 21. Design chart showing role of subgrade elastic modulus ($E_s$) in design of full thickness asphaltic concrete pavements using Chevron Research Method.

Failure the result of excessive tensile strain at the bottom of asphaltic concrete layer (fatigue).

$V_v$ = 3% $V_b$ = 13% $E_1$ = 200,000 psi

$V_v$ = Volume of air voids
$V_b$ = Volume of asphalt residue

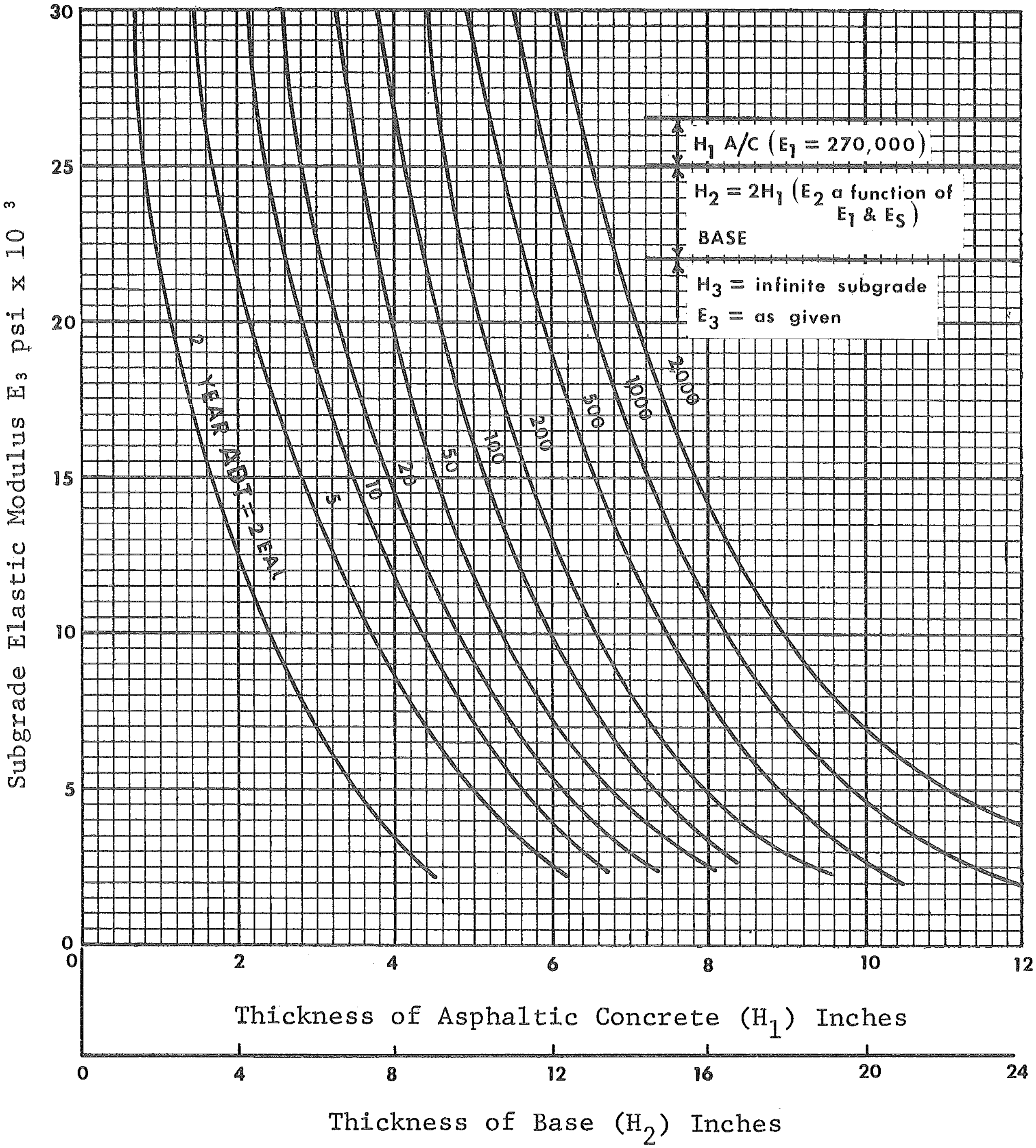



Figure 22. Design chart showing role of subgrade elastic modulus ($E_s$) in flexible pavement design using Kentucky Method.

# Table 16

## Summary of Subgrade Elastic Modulus Values Determined by In-Situ Testing

| Test Location | $E_s$ (from 30"plates @ 30-50) | $E_s$ (from 12"&18" plates | $E_{seis}$ | E=500x CBR | $E_{dynf}$ | $E_{RR}$ | Remarks |
|---|---|---|---|---|---|---|---|
| I-10 Buckeye<br>$\gamma_d$=125pcf<br>w/c=1½%<br>N ≈ 8-13 | 17,500-34,000psi | 29,000-50,000psi | 25,000-42,000psi | - | Range[1] 6000-21,800psi | Median 22,100psi<br>Range 14,100-34,400psi | [1]At time of Dynaflect w/c≈6-10% |
| Lake Pleasant Orange<br>$\gamma_d$≈112pcf<br>w/c≈2%<br>N ≈ 11 | 10,000psi[2] | 54,000psi | 27,000-33,000psi | - | Median(5)* 16,800psi<br>Range 13,000-20,000psi | Median 22,300psi<br>- | [2]$E_s$ from single test believed to be low. |
| Lake Pleasant On-Grade<br>$\gamma_d$=116pcf<br>w/c≈2%<br>N ≈ 8 | 15,000psi[2] | 57,000psi | - | - | Median 19,100psi<br>Range 18,100-23,100psi | - | *Refers to number of values used to determine median |
| Lake Pleasant Fanglomerate Cut<br>$\gamma_d$=119pcf<br>w/c≈1%<br>N ≈ 50/1" | 20,000psi[3] | 25,000psi | 68,000psi | - | Median(5) 16,100psi<br>Range 7900-22,300psi | Median 17,700psi | [3]Estimate based on 18"&24" tests. |
| Cienega Creek<br>$\gamma_d$=135pcf<br>w/c≈4%<br>N = 14 | 14,000psi | 39,000-50,000psi | 53,000-67,000psi | - | Median 22,000psi<br>Range 18,500-27,000psi | Median 20,200psi | |
| Rainbow Valley (near surface)<br>$\gamma_d$=80-100pcf<br>w/c≈1½%<br>N ≈ 1-4 | 6000-10,000psi | 4000-35,000psi | 16,000-[4] 41,000psi | 6000-10,000psi | Median(32) 8400psi<br>Range 6000-18,900psi | - | [4]Probably applies to cemented soil below 1.0 foot. |
| Rainbow Valley (excavation)<br>$\gamma_d$≈103-112<br>w/c≈1½%<br>N ≈ 7-22 | 12,000-26,000psi | 40,000-100,000psi | 26,000-78,000psi | 22,500-28,500psi | Median(15) 16,000psi<br>Range 9500-26,100psi | - | |
| McCormick Ranch (fill)<br>$\gamma_d$=90-100pcf<br>w/c≈2%<br>N = 3 | 13,500-20,000psi | 8000-18,500psi | 21,700psi | - | - | - | |
| McCormick Ranch (fill)<br>$\gamma_d$≈115pcf<br>w/c=3%<br>N = 10 | 15,000-21,000psi | 9000-23,000psi | 21,300psi | 11,500-30,000<br>Median(10) 20,500 | Median(14) 22,000psi<br>Range 11,600-42,500psi | - | |

## Table 18

## Summary of Advantages and Disadvantages of In-Situ Testing Methods

| Advantage | Disadvantage |
|---|---|
| **Plate Bearing Tests** | |
| ·Test is straightforward, easy to run and understand<br><br>·Geometry is uncomplicated; calculation of $E_s$ can be made in accordance with a widely accepted methodology<br><br>·Each test reveals $E_s$ as a function of stress for the range of stresses applied | ·Time required to run each test (2-3 hours for ASTM D1195, 4-6 hours for D1196, longer if secondary compression is significant factor)<br><br>·Once started a test cannot be interrupted<br><br>·Deflection readings are affected by passing traffic<br><br>·Each test provides only one element of data for statistical analysis<br><br>·The response of smaller plates is strongly influenced by heterogeneity of the subgrade, especially where large gravel, cobble, or blocky cemented materials are involved |
| **Refraction Seismic** | |
| ·Definitive value of E modulus can be calculated from $V_s$ and $V_c$; also Poisson's ratio<br><br>·Many tests may be performed in a short time frame<br><br>·Measures the mass response of soil, and is less affected by spatial variations in properties | ·Modulus applies only to low strain levels ($10^{-6}$ and $10^{-4}$); must be reduced by some factor to the stress level of interest<br><br>·Expensive equipment required to record $V_s$. Also requires expert interpretation of wave traces<br><br>·Does not properly account for the loss in stiffness of a subgrade upon increase in degree of saturation |
| **CBR** | |
| ·Test is widely accepted; can be performed by technicians, and equipment is available in nearly every agency<br><br>·Inexpensive<br><br>·Many tests can be performed in a day<br><br>·Stiffness of the upper few inches is measured | ·Contact area is small. Results may be influenced by an imbedded cobble, or blocky cemented matrix |
| **Dynaflect and Road Rater** | |
| ·Considerable data can be collected in a short time; therefore, each particle of data has a low unit cost<br><br>·Technique for conversion of deflection basin to modulus is easily adaptable to computer<br><br>·Quickest way to collect a suite of values for statistical analysis | ·The analysis of deflection bowls and calculation of modulus is empirical and imprecise<br><br>·Deflection values are influenced by internal damping and resonance in soil, subjects which are poorly understood |

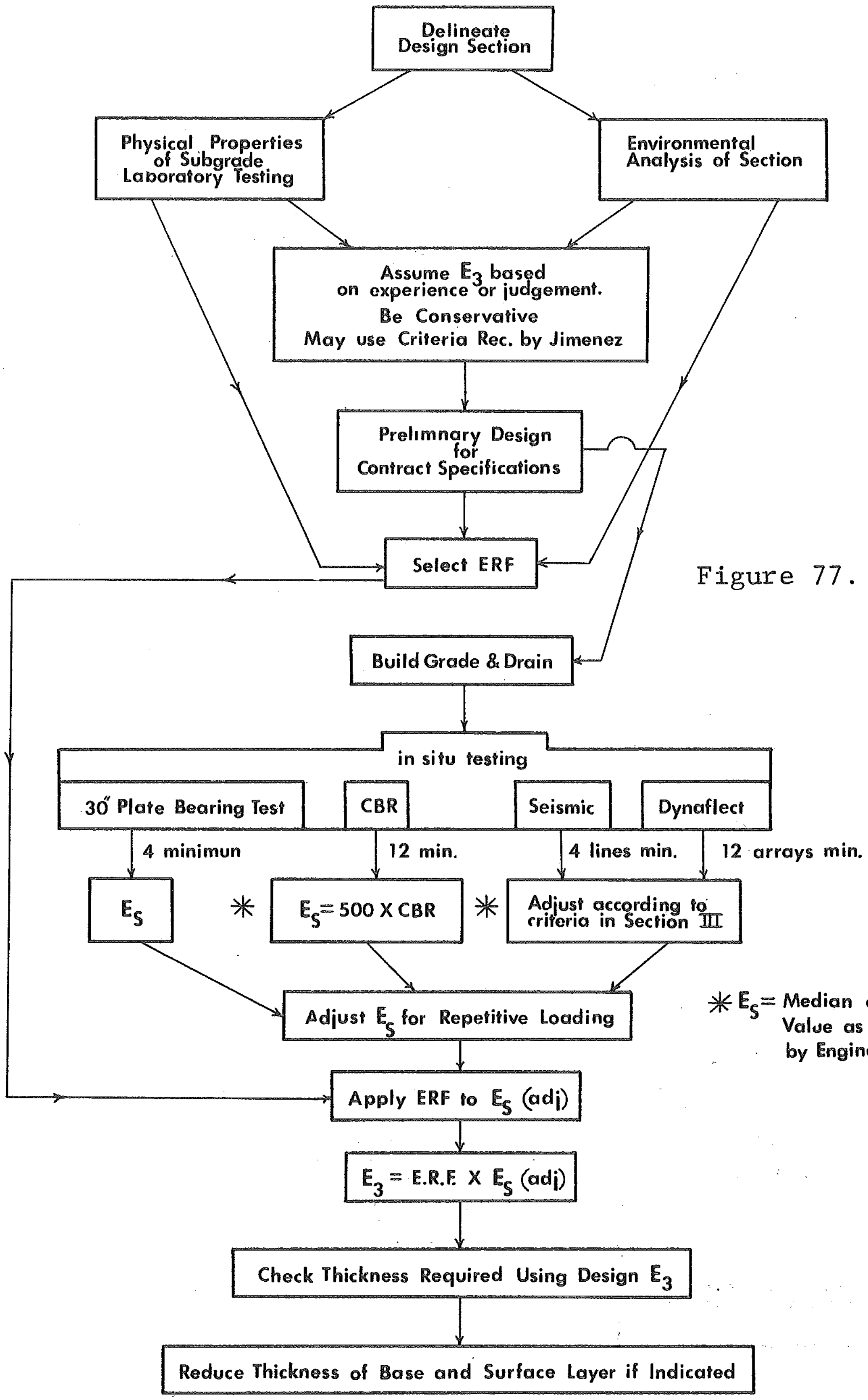



Figure 77. Flow Chart for New Pavement Design