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19.

EVALUATION OF THE AASHO DESIGN METHOD

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ABSTRACT

In 1962 the American Association of State Highway Officials presented a method for the design of flexible highway pavements which was based on a large scale field study. The steps in the development of the basic design method and the assumptions necessary for its application are enumerated and critically discussed in this report.

The concept of highway performance was the basis upon which the Road Test was evaluated. The significance and validity of using performance expressions to estimate pavement life and strength are discussed.

The individual design variables, which include structural coefficients, soil support, traffic intensity and regional factors are presented. Currently available methods for determining each of these variables are examined and evaluated. The importance of selecting appropriate values for the design variables when calculating the pavement life is discussed.

It is concluded that, although it has received widespread acceptance, the AASHO design method has serious limitations. None of the attempts to adopt the procedure to an individual State's requirements have been entirely sucessful. The need for a clearer definition of material

properties, and their relationship to the statistically based AASHO design variables, is indicated.

I. INTRODUCTION

In 1962 the American Association of State Highway Officials, in cooperation with a wide variety of interested states, institutions, industries and agencies, completed a comprehensive, full-scale highway study. The analysis and subsequent evaluation of the observed performance of the test sections at the Road Test led to the development of the AASHO design method. The resulting design equations and charts were intended to provide the entire country with an efficient and practical design method.

The Road Test experiment design was constructed so that relationships between pavement design, number of applications of load and performance could be established. Special studies were focused on finding the in-place behavior of individual types of materials commonly used in highway construction. Attention was also directed towards including the influences of environmental factors and embankment strength on pavement life.

General use of the AASHO design method requires that specific structural coefficients and soil support terms be assigned to the pavement and subgrade materials. These terms reflect a material's strength and suitability in the highway. In addition, the effects of environmental conditions must be assessed and represented by a regional factor. Finally, the traffic anticipated over the life of the roadway must be estimated and reduced to a number of applications of a standard reference axle load.

The history and development of the Road Test equations, and their extension to performance studies, will be discussed. The background and significance of the required design values, as well as current methods of obtaining them, will be discussed and evaluated.

II. DEVELOPMENT OF THE AASHO DESIGN METHOD

2.1 The AASHO Road Test

The AASHO Road Test was a highway research project sponsored by the American Association of State Highway Officials, in conjunction with many private and public sponsors, for the purpose of examining the behavior of typical highway pavements and structures under full scale conditions.

A carefully planned experiment design was developed in which both flexible and rigid pavements of known layer thicknesses were constructed in six traffic loops in order to examine the interrelations between thicknesses, and magnitude and frequency of loading. A complete description of the road test facilities are given in the Highway Research Board Special Report Nos. 61B and 61C, (1962).

The scope, magnitude and duration of the Road Test greatly exceeded any such previously completed project. The efforts to carefully control the material properties and construction procedures at the site, as well as to fully develop the experiment design and provide thorough and consistent testing procedures have been well documented by many researchers (Shook and Fang, 1961; HRB Special Report 61E, 1962).

First among the list of carefully chosen Road Test objectives stated by the National Advisory Committee was to determine the significant relationships between load and performance for various thicknesses of uniform pavement components constructed on a uniform basement soil. The results were then to be examined in light of variations in climate, soil type, materials, construction practice and traffic type.

To accomplish this objective, the Advisory Committee chose to develop the concept of performance in terms of a highway's capacity to serve the traveling public. The level of quality, or serviceability, was based on a subjective, zero to five rating scale established from rider reaction to a particular roadway. The performance of a road may then be represented by the serviceability history as a function of the loading history. For example, good performance is typified by continued high serviceability under many load applications.

In order to apply the serviceability concept to the actual Road Test pavements, rapid, simple and reproduceable test methods were developed to objectively rank a pavement's current riding quality or present serviceability index (PSI or p_t), in a manner which correlated with the subjective rating system.

The physical aspects selected as being indicative of the road surface quality were slope variance, rutting, patching and cracking. Actual test procedures used at the Road Test are detailed in HRB Special Report 61E (1962).

Test vehicles with known axle configurations and loads were cycled over each pavement structure at known frequencies. Periodically, at biweekly intervals called index days, the PSI of each section was determined. Traffic was continued until the PSI dropped to a value of 1.5, indicative of a very low level of serviceability, or until the Road Test was terminated. Thus, a complete performance history of a wide range of combinations of types and thicknesses of road pavements were obtained.

2.2 Road Test Results

The method whereby performance of flexible pavements is related to roadway design and number of load applications is examined. The main aspects of this are found in Appendix G of HRB Special Report 61E (1962).

Performance curves were obtained for each section by plotting the observed PSI values against the index day or the accumulated number of load applications obtained at each particular index day, as shown in Fig. (1). The shape or trend of the curve represents the performance of the section. In order to eliminate the seasonal effects, the accumulated number of loads was adjusted or weighted prior to developing the curves. The assumed weighting functions tended to overcome the fact that the effect of the loads was related to the moisture and temperature of the sections.

The objective of the Road Test Committee was to develop a mathematical model which described the performance record curves obtained from all sections. It was assumed that the loss of performance was some power function of axle load application, expressed as

$$p_o - p_t = K\, W_t^{\beta} \qquad (1)$$

where p_o is the initial serviceability index, p_t is the present serviceability index and W_t is the accumulated axle loads (both at time = t), and K and β are terms related to both the load and the section design.

At the conclusion of testing at each section, whether by p_t reaching the terminal value of 1.5 or by termination of the Road Test, the following relationship existed:

$$p_o - p_1 = K\, (\rho)^{\beta} \qquad (2)$$

where ρ is the terminal number of axle load applications at a terminal value of PSI equal to p_1.

Solving Eq. (2) for K and substituting the resulting value into Eq. (1) yields:

$$p_t = p_o - (p_o - p_1)\left(\frac{W_t}{\rho}\right)^{\beta} \tag{3}$$

which expresses p_t at any intermediate time in terms of initial and final values of PSI and intermediate and final loads.

Rearranging Eq. (3) and converting to logarithmic form results in,

$$G = \beta\ (\log W_t - \log \rho) \tag{4}$$

where G is defined as the known quantity:

$$G = \log \left(\frac{p_o - p_t}{p_o - p_1}\right) \tag{5}$$

Values for β and ρ for each section were then obtained from slope and intercept, respectively, of the linear plots resulting from Eq. (4).

β was then assumed to be related to the magnitude of applied loads and the pavement design as:

$$\beta = \beta_o + \frac{B_o\ (L_1 + L_2)^{B_2}}{(a_1 D_1 + a_2 D_2 + a_3 D_3 + a_4)^{B_1}\ L_2^{\ B_3}} \tag{6}$$

and ρ expressed as

$$\rho = \frac{A_o\ (a_1D_1 + a_2D_2 + a_3D_3 + a_4)^{A_1}\ L_2^{\ A_3}}{(L_1 + L_2)^{A_2}} \tag{7}$$

where a_1, a_2, a_3 = structural coefficients related to material strength; a_4 = a coefficient related to the subgrade strength; D_1, D_2, D_3 = layer thicknesses, in inches, of the surface, base and subbase, respectively; L_1 = nominal axle load in kips; L_2 = an axle code, (1 for single axles, 2 for tandem axles). The remaining terms are mathematical constants used in the analysis.

The exact method of solving Eqs. (6) and (7) is beyond the scope of this discussion. However, statistical analysis of the Road Test data, using linear regressional analysis techniques to obtain "best fits" of the observed information, allowed the effectiveness of various pavement components to be ranked in terms of a_1, a_2, a_3.

The reduction techniques reduced Eq. (6) to

$$\beta = 0.40 + \frac{0.081\ (L_1 + L_2)^{3.23}}{(SN + 1)^{5.19}\ L_2^{\ 3.23}} \tag{8}$$

and Eq. (7) to

$$\rho = \frac{10^{5.93}\ (SN + 1)^{9.36}\ L_2^{\ 4.33}}{(L_1 + L_2)^{4.79}} \tag{9}$$

where SN is the structural number as defined by

$$SN = a_1D_1 + a_2D_2 + a_3D_3 \tag{10}$$

A significant result from the AASHO Road Test is the statistical evaluation of the structural coefficients (a_1, a_2, a_3) which reflect the in-place behavior of each pavement layer (D_1, D_2, D_3).

2.3 Design Equations

A main objective of the AASHO Committee was to transform the results of the performance study into a useful design method (Langsner, Huff & Liddle, 1962). The method considers not only pavement design and number of load applications, but also parameters reflecting both subgrade soil support and regional effects.

A relationship between number of axle loads, structural number and performance was obtained by adopting an 18^k single axle load as a standard and solving Eqs. (8) and (9), respectively, for β and ρ. These two quantities were then substituted into Eq. (4) which could then be reduced and rearranged as

$$\log W_{18} = 9.36 \log (SN + 1) - 0.20 + \frac{G}{0.40 + \dfrac{1{,}094}{(SN + 1)^{5.19}}} \qquad (11)$$

where W_t is now noted as W_{18}.

Equation (11) represents the mathematical development of the Road Test results which predicts the number of 18^k axle load applications, W_{18}, required to reduce the serviceability from an initial high of p_o to any intermediate value, p_t, for a pavement having a structural number of SN.

The next step in formulating the design procedure was to expand Eq. (11) to include soil support and regional influences beyond the limited conditions which prevailed at the Road Test site.

The AASHO Committee realized that the behavior of a road is significantly effected by environmental factors such as temperature, rainfall and drainage conditions. In order to relate the test results obtained from the single test site to a wide variety of possible conditions elsewhere in the country, the Design Committee developed the concept of a regional or environmental factor. This term would modify the fundamental design equations for national use.

Although the exact relationship was not established, the AASHO Committee assumed that the destructive effect of accumulated 18 kip axle loads, W'_{18}, on any highway could be related to a comparable level of effectiveness due to the accumulated 18 kip axle loads, $\dot{W}_{18}$, at the test site, by a proportionality or regional factor, R, as

$$W'_{18} = \frac{1}{R} W_{18} \tag{12}$$

or in logarithmic form as

$$\log W'_{18} = \log \left(\frac{1}{R}\right) + \log W_{18} \tag{13}$$

It was tentatively estimated that the value of R ranged from 0.2 to 5.0 as the road bed strength decreased due to environmental factors.

In order to expand the design method to encompass soil support conditions beyond the single roadbed constructed at the AASHO Road Test, the Design Committee established a 10 point soil support scale with the intent that soils of different supporting characteristics could be evaluated and correlated with the scale.

A soil support value, (SS = 3), was arbitrarily assigned to the roadbed which underlaid a typical pavement with a structural number of 1.98. The total number of load applications, for typical pavements, was distributed over an assumed 20 year design period, resulting in a figure of 2.5 equivalent 18 kip daily single axle applications.

Special studies of particularly heavy crushed stone bases indicated that an asphaltic layer with a structural number of 1.98 on a roadbed with supporting characteristics of crushed stone would carry 600 and 1000 18^k applications per day to terminal serviceabilities of 2.5 and 2.0, respectively. A soil support value of 10 was assigned to the hypothetical high support roadbed.

Thus, the two conditions of soil support, load applications and structural number allowed a scale to be set up by assuming a linear distribution between the values of 3 and 10.

If the effect of axle loads is assumed to vary with some function of the soil support, f(SS), then

$$W_{18}'' = f(SS)\ W_{18}' \tag{14}$$

or in logarithmic form

$$\log W_{18}'' = \log f(SS) + \log W_{18}' \tag{15}$$

where W_{18}'' and W_{18}' are two values of accumulated axle loads which have the same ability to deteriorate a given pavement constructed on roadbeds of soil support SS_i and SS_o, respectively.

The soil support function is assumed to be related to the soil support value as,

$$f(SS) = 10^{k'\ (SS_i - SS_o)} \tag{16}$$

where K' is a proportionality constant. In logarithmic form, Eq. (16) is

$$\log f(SS) = K'\ (SS_i - SS_o) \tag{17}$$

Again considering the two values of $W'_{18} = 2.5$ and $W_{18}" = 1000$ for accumulated axle loads corresponding to $SS_o = 3$ and $SS_i = 10$, the value of f(SS) from Eq. (14) was found to be 400. Applying this value, as well as the scale values of soil support, to Eq. (17) results in a proportionality constant of 0.372.

The general relationship for any soil support value of SS, referenced to the AASHO roadbed, becomes

$$\log f(SS) = 0.372\ (SS - 3.0) \tag{18}$$

and the variation in allowable loads may be expressed by Eq. (15) as

$$\log W_{18}" = 0.372\ (SS - 3.0) + \log W_{18}' \tag{19}$$

where $W_{18}"$ corresponds to a roadbed soil support of SS and W_{18}' corresponds to any roadbed with a soil support of 3.0.

Therefore, to weight or adjust a value of allowable load applications at any location, the term log W_{18} in Eq. 11 has to first be modified for soil support conditions by Eq. (19) and the resulting value modified for regional conditions according to Eq. (13).

Combining Eqs. (19) and (13) with Eq. (11) results in the final AASHO design formula

$$W_{18}'' = \frac{(SN + 1)^{9.36} \cdot 10^{0.372\ (SS - 3.0)} \cdot 10^{\left[\frac{G}{0.40 + \frac{1,094}{(SN + 1)^{5.19}}}\right]}}{R \cdot 10^{0.20}} \tag{20}$$

or in logarithmic form,

$$\log W_{18}'' = 9.36 \log (SN + 1) + 0.372\ (SS - 3.0) + \log \left(\frac{1}{R}\right) - 0.20 + \frac{G}{0.40 + \frac{1,094}{(SN + 1)^{5.19}}} \tag{21}$$

The resulting design charts, as shown in Fig. (2), were constructed for specific limiting serviceabilities (Langsner, Huff and Liddle, 1962). It was reasoned that terminal values of PSI (or p_1) for high type and secondary roads of 2.5 and 2.0, respectively, would result in satisfactory service over the design life.

A recent independent study sponsored by HRB verified the AASHO design procedure and charts within the scope of the original assumptions (McCullough and Van Til, 1968).

2.4 Enumeration of Variables

The design chart, Fig. (2), can be readily used to obtain required structural numbers for proposed pavement provided that the basic assumptions and limitations of both the method and input information are understood. For convenience, a 20-year design life was assumed in order to reduce the total allowable axle loads to daily load applications. However, since the basic design equations are in terms of total accumulated axle loads, any other design life period may be used provided that the total number of load applications is known.

A list of required design variables is as follows:

1. Structural coefficients based on material properties.
2. Layer thicknesses.
3. Daily 18^k equivalent axle load applications.
4. Soil support based on subgrade strength.
5. Regional factor based on environmental conditions.

The success of the resulting pavement in carrying the required traffic through reasonable values of serviceability over the design period will depend upon the accuracy of the variables listed above. Current thinking regarding the variables and existing methods for evaluating them will be examined in subsequent chapters.

III. PERFORMANCE

3.1 Uses for the Performance Concept

The importance attached to the concept of performance by highway researchers was suggested in Chapter II. The fundamental ideas underlying serviceability and the actual development of a practical rating system have been established (Carey and Irick, 1960). A great deal of emphasis has been placed on the relationship between initial pavement design and the deterioration resulting from load applications.

One major area of highway research following the Road Test was the development of mathematical formulations which describe the performance curves obtained from the various test sections. In general, these equations relate values of performance and wheel load applications to various parameters. In turn, attempts have been made to evaluate these parameters in terms of initial values of layer thickness and composition, soil support and climate. The AASHO equations developed in Chapter II are but one of the existing models developed to describe the performance curves.

Three general areas of use have been established for the performance relationships. The first is to estimate pavement life based on a relatively few number of observed serviceability ratings. The second is to relate performance to structural design. Finally, measures of composite strength have been correlated to serviceability with the hope that these studies will aid in the basic understanding of roadway behavior.

3.2 Estimating Pavement Life

There are numerous advantages to both researchers and maintenance forces if the life expectancy of a road can be approximately determined by a relatively few simple measurements taken years in advance of predetermined terminal conditions. Several mathematical models will be presented and their applicability to the problem will be examined.

The general AASHO equation, as expressed previously, is

$$p_t = p_o - (p_o - p_1)\left(\frac{W_t}{\rho}\right)^{\beta} \tag{3}$$

A somewhat simpler model was developed by the Asphalt Institute after an independent analysis of the Road Test data (Painter, 1962). It was originally presented as

$$p_t = p_o\, e^{-\frac{bW_t}{10^6}} \tag{22}$$

where b is a deterioration rate parameter similar to β of Eq. (3).

A model of similar form was advanced by Irick in the preliminary satellite study guidelines (Irick and Hudson, 1964) as

$$p_t = p_o \, 10^{-\left(\frac{W_t}{r'}\right)^{b'}} \qquad (23)$$

where b' and r' are terms dependent upon the highway design.

Converting Eq. (3) into logarithmic form and rearranging in terms of log W_t, the performance index, the AASHO equation becomes:

$$\log W_t = \frac{1}{\beta} \log \left(\frac{p_o - p_1}{p_o - p_t}\right) + \log \rho \qquad (24)$$

similarly, from Eq. 22 for Painter's equation,

$$\log W_t = \log \log_e \left({}^{p_o}/_{p_t}\right) - \log b + 6 \qquad (25)$$

and from Eq. 23 for Irick's equation,

$$\log W_t = \frac{1}{b'} \log \log \frac{p_o}{p_t} + \log r' \qquad (26)$$

The similarity between the formulas can readily be seen and common practice is to develop linear equations of the form,

$$\log W_t = B \, f(p_o, p_t) + A \qquad (27)$$

whereby appropriate plotting yields both the slope, B, and the intercept, A, of the straight line.

The object of prediction studies is to obtain observed values of serviceability corresponding to known values of accumulated axle loads. The manner in which the equations are used, and the resulting accuracy of the answers, depends upon the number of observations and the proper conversion of mixed traffic to equivalent axle loads.

If one observed data point on the performance plot is known, values of p_o and B need to be established. It may be that the initial serviceability is known, but it is more likely that this value will have to be estimated either by assuming the average value of 4.2 found for flexible pavements at the Road Test or assumed from prior experience. The weaknesses of assuming p_o have been pointed out by the Virginia Satellite Study Program (Vaswani, 1967). The slope B, for each particular model, may be assumed from the Road Test data. Irick indicates that a suitable approximation for the B term in Eq. (24) based on the AASHO results is 1.0 for flexible pavements. However, actual determinations of B for various pavements in Minnesota indicate a wide range of scatter (Kersten and Skok, 1968).

With these inherent drawbacks in mind, values of p_o and slope are assumed and the intercept term, A, calculated. Then, with both A and B defined, a desired terminal serviceability, generally about 2.5, is used to solve the basic equations for W_t.

The need to estimate B is eliminated if two or more data points are obtained. Irick presented an expression for the performance index for multiple data points based on Eq. (26), as

$$\log W_t = \bar{Y} + B_1' \left[\log \log \frac{p_o}{2.5} - \bar{X}\right] \tag{28}$$

where $\bar{Y}$ is the average of observed values $Y = \log W_t$ and $\bar{X}$ is the average of the observed values $X = \log \log {}^{p_o}/_{p_t}$. B_1' is defined as:

$$B_1' = \frac{\Sigma\ (Y - \bar{Y})\ (X - \bar{X})}{\Sigma\ (X - \bar{X})^2} \tag{28A}$$

Equation (28) presupposes known values of initial serviceability and a terminal serviceability of 2.5.

Vaswani demonstrated a method of establishing p_o based on a linear form of Painter's equation when several data points are available.

In general, the serviceability of a road must deteriorate at least one full point below the initial value before successful evaluation of the "road life" may be obtained. The Minnesota satellite has begun analyzing observed and estimated serviceabilities. Kersten points out that within a relatively short period of three years the results have not proved encouraging. However, the final verification of these techniques will require many years of study.

3.3 Performance as Related to Structural Design

The final expressions of the AASHO Road Test analysis, Eqs. (8) to (9), indicate that the variables ρ and β may be sucessfully predicted by mathematical models which contain basic material type and layer thickness parameters.

Additional analysis of the AASHO Road Test data by HRB resulted in the following performance equation (Irick and Hudson, 1964)

$$p_t = p_o \, 10^{-\left[\frac{W_{18}}{R^4 D^8}\right]^{b''/4}} \qquad (29)$$

in which the influence of the regional factor, R, and a design term, D, have been added to Eq. (23). The design term is expressed as

$$D = a_1 r_1 D_1 + a_2 r_2 D_2 + a_3 r_3 D_3 + r_4 \qquad (30)$$

where r_1 to r_4 are ratios of the relative strength of a particular material from layer 1 to layer 4 as referenced to the test site.

Painter's work also was directed towards breaking down the deterioration rate parameter into design and climate factors (Painter, 1965). The original form of the performance equation

$$\ln {}^{p_o}/_{p_t} = b\ W_t \tag{31}$$

was revised to

$$\ln {}^{p_o}/_{p_t} = b_o\ W_t{}^* \tag{32}$$

in which the design related factors were isolated in the quantity b_o as

$$\ln b_o = a_o' + a_1'D_1 + a_2'D_2 + a_3'D_3 + a_4'L' \tag{33}$$

where a_1' to a_3' in the above equation are Painter's derived structural coefficients, D_1 to D_3 are the respective layer thicknesses, a_4' is the subgrade strength coefficient, L' is dependent upon the axle load and configuration and a_o' is a mathematical term. Climate or regional factors were isolated in the weighed traffic count, $W_t{}^*$.

Thus, a great deal of effort has gone into relating structural design to performance. Within the bounds of the AASHO Test data it is possible to develop coefficients and quantities which reflect material strength, layer thickness, soil support and regional effects. These factors may be tied together into various equations which give reasonable estimates of the number of wheel loads required to reduce a roadway to a given level of serviceability.

However, the methods of analysis used require a large number of sections with carefully selected variations in layer thicknesses and material in order that significant trends develop and can be analyzed. Unfortunately, conditions such as these have only been available at the Road Test. The complete reduction of performance data to yield structural coefficients and allowable axle loads is not practical for satellite study programs. Current research trends are toward finding this type of information from other sources such as in-situ or laboratory strength tests (Seed, Mitry, Monismith and Chan, 1967; Coffman, Ilves and Edwards, 1968).

3.4 Relationship between Performance and Composite Strength

The AASHO Road Tests presented relationships between number of wheel loads and measurements of composite strength throughout the life of the pavements (Irick and Hudson, 1964).

In general form

$$p_t = A_o' - A_1' \log S \tag{34}$$

where A_o' and A_1' are numerical constants and S is a quantity, such as the Benkelman Beam deflection, which reflects total composite strength. This relationship will be examined more closely in Chapter IV, but is presented to introduce the fact that Benkelman Beam deflections can be related to wheel load applications.

Pavement behavior analysis at the Texas Transportation Institute has related Benkelman Beam deflections to initial pavement design through the use of Painter's basic performance equation (Schrivner and Moore, 1966).

Equation 31 is commonly expressed as

$$\log {}^{P_o}/_{P_t} = b\, W_{18} \tag{35}$$

where Painter defined the deterioration parameter, b, as a function of design, type and magnitude of load, soil support and climate. Schrivner assumed b varied only with pavement deflection, d, as

$$b = 10^{A_o''}\, d^{A_1''} \tag{36}$$

where A_o'' and A_1'' are constants which can be determined from the Road Test deflection data.

A performance expression Q_L was defined as

$$Q_L = \log W_t - \log\log ({}^{p_o}/_{p_t}) \tag{37}$$

or more commonly expressed as

$$Q_L = \log \left[\frac{W_t}{\log p_o - \log p_t}\right] \tag{38}$$

Q_L was then found to be related to the Road Test data as

$$Q_L = 9 - 3.2 \log d \tag{39}$$

The basic mathematical statement for relating performance to design and region was assumed as

$$Q = B'* TDI + C_r \tag{40}$$

where Q is the performance reduced to 18 kip equivalent axle loads, B' is a constant, C_r is a regional coefficient and TDI is the Texas Design Index defined as

$$TDI = S_1D_1 + S_2D_2 + S_3D_3 + 1 \tag{41}$$

S_1 to S_3 are strength coefficients determined by test data.

Thus, a method has been established which uses the basic concepts of performance trends and behavior in relating composite strength data to the allowable design.

3.5 Methods of Obtaining the Present Serviceability Index

The serviceability of a roadway section at the Road Test was found to be related to the slope variance, rut depth and amount of cracking and patching. Descriptions of the AASHO longitudinal profilometer for measuring slope variance, the transverse profilometer and gauges used to obtain the rut depth and methods for obtaining cracking and patching have been well documented (Carey, Huckins and Leathers, 1962; HRB Special Report 61E, 1962).

Many recent advanced and alternate methods for determining the above mentioned quantities have been suggested (Yoder and Milhous, 1944; Holbrook, 1969; Phillips and Swift, 1969). The object of such work is to determine the PSI rating of a road as rapidly as possible with accurate, relatively inexpensive equipment. A list of the commonly used devices is given is Table 1.

IV. EVALUATION OF STRENGTH OF PAVEMENT COMPONENTS

4.1 Basis for Structural Coefficients

The evaluation of the structural coefficient terms was one of the most significant results of the Road Test. The analysis of the test data produced definite numerical evaluations of the contributing effects of various types of materials within the roadway. The concept of structural coefficients and their use to determine the structural number of a pavement, as expressed by Eq. (10), has become an integral part of the AASHO design method. The essential idea is that different road building materials possess varying characteristics which, when assigned a numerical coefficient, may be properly related to the overall design. For everyday use of the AASHO design method, the correct coefficient values are of immediate importance.

The origin of the structural coefficients lies within the statistical analysis of the performance data gathered at the Road Test. The individual values, as reproduced in Table 2, are the result of mathematical evaluation rather than direct determination of individual physical properties. There is a strong tendency to consider the structural coefficients as being specific and fundamental material properties which may either be found or assumed for design purposes. However, close examination of the background of the coefficients indicates that they are inherently tied directly to the Road Test pavements. Ignoring this fact will result in improper use beyond the original intent and meaning of the values.

The structural coefficients are valid only for layered systems arranged as those at the Road Test, or, in other words, the relative positions of the surface, base, subbase and subgrade must be maintained. Further, the values are dependent not only upon material composition but also upon the layer thickness. In addition, the relative proportions of surface, base and subbase must be held to within the limits of the sections examined at the Road Test.

The loading conditions at the Road Test were very well defined in terms of speed, magnitude, direction of travel, axle configuration and wheel contact area. Control of these factors was considered essential to the success of the Road Test. Subsequent research, both on a theoretical and experimental basis, has shown that the material properties also vary with the above conditions (Finn, Coffman, 1967; Ilves and Edwards, 1968).

The values given in Table 2 are based on weighted axle load applications. If the actual number of axle loads, uncorrected for environmental effects are used, another set of structural coefficients are obtained (HRB Special Report 61E, 1962). Therefore, the coefficients are dependent not only upon environmental factors at a proposed highway location, but also upon how well the factors were initially evaluated and used in the basic analysis.

The structural coefficients assumed for materials used at the test site, and those calculated or assumed for materials used in other locations, must be regarded with care since their correct use ultimately involves many factors beyond individual physical properties.

4.2 Evaluation of the Structural Coefficients

The intent of the Design Committee was to provide structural coefficients for many basic road building materials which would serve the majority of design situations. Furthermore, the individual satellite study programs were to verify or modify the original AASHO values and develop new coefficients for other materials used throughout the country (Irick, 1964; Irick and Hudson, 1964). However, due to their background, the direct evaluation of the structural coefficients for use in the AASHO design method is not practically possible.

4.2.1 Correlation Studies

Perhaps the simplest and most straight-forward method of evaluating the structural coefficients is by correlation studies. In general, standard laboratory tests measuring readily obtainable properties, such as cohesion, shear strength, stability or bearing strength, are performed on materials similar to the Road Test. The tests are repeated on materials of varying qualities used by the particular state. Ratios, relative scales or graphs are then established.

Many states, such as Illinois, performed tests on the actual components used at the Road Tests. Relative ratings for stabilized base courses were developed by knowing, 1) coefficients and laboratory values for AASHO stabilized materials, and 2) coefficients and laboratory values for similar, but unstabilized, AASHO materials. Graphs for finding the coefficients of other stabilized bases were then constructed based on the two known reference points (Chastain and Smith, 1965).

An extensive survey of current methods for establishing or modifying the coefficients indicates a variety of approaches for analyzing the layer components (McCullough and Van Til, 1968).

The quality of asphaltic surface materials is commonly related to the Marshall Stability test. Coefficients for base materials stabilized with asphaltic or bituminous materials are determined on the basis of Marshall Stability, Texas triaxial, triaxial and cohesiometer tests. In addition, variables such as composition and abrasive properties are sometimes included. Cement stabilized bases are commonly evaluated on the basis of 7-day unconfined compressive strength. Untreated granular bases and subbase are related to R-value, CBR and triaxial tests.

4.2.2 Estimation and Judgement

The AASHO Guidelines emphasize the fact that rationalization, judgement and experience must be used in order to successfully apply the Road Test coefficients. Many states, such as Illinois, Pennsylvania and New Jersey, use the assigned values without modification, whereas others prefer to reduce the coefficients in order to compensate for adverse conditions such as lack of high quality material and substandard construction techniques.

New materials are often ranked strictly by judgement. For example, Massachusetts uses a crushed stone base penetrated with asphalt. The resulting bonded mix is stronger than unstabilized crushed stone but not as effective as a well-graded black base. A structural coefficient for the penetrated stone base was selected as being the numerical average of the coefficients previously evaluated by the AASHO Committee for crushed stone and black base (Tons, Chambers and Kamin, 1965).

In view of the fact that the structural coefficients depend on a great deal more than basic material properties, individual use and modification of the values is and will continue to be based strongly on individual judgement and long term experience with the AASHO design method.

4.3 Direct Evaluation of Material Equivalencies

Due to the lack of readily available, straightforward methods of evaluating pavement structural coefficients, a great deal of research is directed towards determining equivalencies or relative rankings. The purpose of these laboratory and field tests is to isolate some specific property or set of properties which reflect the materials inherent strength. These test values are then used as a basis for evaluating the suitability of the material within a pavement structure. Equivalency tests are used both to rank dissimilar materials with one another, or, more commonly, to rank or rate similar materials. Standard quality control tests would fall into the latter classification.

4.3.1 Laboratory Methods

There are a variety of physical properties which relate to material strength. In addition, there are many factors which directly affect these properties. The chief advantage of laboratory testing is that the test conditions may be closely controlled, allowing individual contributing factors to be isolated and analyzed. Many of the properties sought, and techniques used, are similar for various types of materials. For this reason, methods rather than specific layer materials will be discussed.

4.3.1 a. Moduli Tests

Moduli of materials are of prime importance for they are directly related to the load, stress, and deformation properties of a material. The objective of these studies is to define a relationship or moduli which realistically relates some loading condition to the resulting strain. These values are then used to directly rank material effectiveness or used to calculate known field load-deflection conditions based on some assumed layer system.

An extensive series of laboratory tests have been carried out by the Asphalt Institute in which a number of moduli were examined (Kailas and Riley, 1967). They recognized the importance of using dynamic or repeated load tests in order to obtain conditions dynamic closely related to actual highway behavior.

The dynamic complex modulus, $|E^*|$, for asphaltic surfaces and stabilized bases is expressed as:

$$|E^*| = {}^{\sigma_o}/_{\varepsilon_o} \qquad (42)$$

Where σ_o is the applied vertical stress on a simple, unconfined sample and ε_o is the resulting vertical strain as recorded by SR-4 strain gages mounted on the specimen.

The dynamic stiffness modulus, E_s, was found by loading small beam samples of stabilized materials under dynamic conditions. The modulus,

$$E_s = \frac{P\ a\ (3\ l^2 - 4a^2)}{48\ Id'} \tag{43}$$

is a function of the applied load, P the beam dimensions, l and a moment of inertia, I and the observed deflection, d'.

A third repeated load parameter, the modulus of resilient deformation, is a dynamic triaxial test. The modulus is expressed as

$$M_R = \frac{\sigma_d}{\varepsilon_r} \tag{44}$$

where σ_d is the repeated deviator stress and ε_r is the recoverable axial strain. Kailas and Riley found the following relationship existed for the resilient modulus;

$$M_r = K''\ \sigma_3^{\ N} \tag{45}$$

where K" is a proportionality constant, σ_3 is the lateral confining pressure and N is a material constant. Similar studies of a limited series of resilient moduli tests on surface base and subgrade material produced the same relationship (Seed, Mitry, Monismith and Chan, 1967). A second expression,

$$M_r = K''' \, \theta^{N'} \tag{46}$$

was also found by the latter experimenters, where K''' and N' are constants, $\theta = \sigma_1 + \sigma_2 + \sigma_3$, σ_1 is the vertical stress and σ_2 and σ_3 are the lateral stresses.

The laboratory determined moduli are intended to show the stress-strain relationship which exists for a particular material after many repêtitions of load. It has been found that the behavior may be considered essentially elastic after many loading cycles, and as many as 10^4 to 10^5 applications are frequently applied to reach conditions which are assumed to exist in highway pavements.

More significantly, the moduli values obtained by any testing procedure are not constant. Factors such as temperature, water content, magnitude, frequency and duration of applied load, lateral pressure (if used), thixotropy or sample age, material type, and degree of compaction are all related to the moduli values. The importance of this is that, if the values are to be used for ranking purposes, or in subsequent analysis, the initial conditions which exist in an actual pavement system must be carefully and realistically defined. Although parallel trends are observed, the moduli values from the various tests do not agree due to the differences in testing techniques.

An interesting addition to the dynamic complex modulus test is that Poisson's ratio, μ, may be readily obtained by mounting an additional strain gage horizontally on the sample. The ratio was found to be frequency and temperature dependent.

4.3.1 b. Seismic Tests

A relatively new technique of measuring seismic waves provides an alternate method for the laboratory determination of fundamental physical properties. The velocity of a compression wave passing through an elastic material is directly proportional to its elastic properties. The exact nature of seismic measurements is not completely understood, but the resulting measured velocities do serve as a method for ranking the elastic behavior of a variety of materials (Schrivner and Moore, 1966).

4.3.1 c. Additional Laboratory Tests

The standard laboratory tests, such as Marshall Stability, R-value, triaxial and CBR, (See Sec. 4.2), may be used to obtain relative rankings of material strength. However, the fact must be kept in mind that these tests may not reflect the same in-situ strength properties which exist in a highway. A second serious drawback to the conventional tests is that they are not generally applicable to all road building materials.

Additional tests not mentioned in Sec. 4.2 which may be used to obtain relative strengths of stabilized materials are the Hveem Stability, ultimate tensile and splitting tensile tests. Numerous specialized test methods for asphaltic materials, such as creep, relaxation and viscosity tests, have been reported (Finn, 1967).

4.3.2 Field Test Methods

There are several significant advantages in field testing as contrasted to laboratory testing. The final objective of this form of research work is to evaluate the behavior of highways. In this sense, field tests tend to be more realistic in that they obtain some form of response from an actual pavement system which reflects, in many cases, the total environment of the structure. It is difficult to obtain the same degree of similarity to actual field conditions by laboratory testing. Factors such as layer interaction, temperature changes and confining pressure gradients across the system are very complex. If not completely understood or isolated by a field testing method, their effect is at least included in the results. Field testing, in many instances, also avoids sample size problems or scale factors needed to relate laboratory tests to field conditions. Since some field testing procedures are applicable to all layers, the discussion of those methods will also include evaluation of the subgrade layer.

4.3.2 a. Vibratory Methods

The principle behind vibratory or seismic testing, as noted in Sec. 4.2.2 b, has been adapted for field use in order to obtain in-situ properties of material layers. The first property which may be examined is the velocity of compression wave transmission. As previously stated, the velocity is related to the elastic properties of the material. The dynamic modulus of elasticity may be computed as,

$$E = K_o \gamma V^2 \tag{47}$$

where V is the wave velocity, γ is the density and K_o is a proportionality constant (Jones, 1958).

An approximate method for correlation between the dynamic modulus of elasticity and field CBR tests on subgrade material has been established (Heukelom and Foster, 1960), where

$$E = 100 \text{ CBR} \tag{48}$$

Similar correlation studies have indicated good agreement between vibratory techniques and the use of large sized plate-load equipment.

A second pavement property, the dynamic stiffness, has been obtained by vibrational methods and expressed as

$$S' = {}^{F}/_{Z} \tag{49}$$

where S' is the dynamic stiffness, F is the applied dynamic force and Z is the resulting pavement displacement. The total stiffness of a layered system may be related to 1) the elastic stiffness and 2) the moving mass and damping effects. The elastic stiffness, R', is independent of frequency and is more closely related to actual highway load-response conditions (Heukelom, 1961).

R' is related to the elastic properties of a roadbed as

$$R' = q\, a'\, E \tag{50}$$

where q and a' are factors which depend upon Poisson's ratio and the stress distribution beneath the loaded area, and E is the modulus of elasticity of a soil. The influence of a layered pavement on the dynamic stiffness is expressed as

$$R_p' = \phi \; R_s' = \phi \; q \; a' \; E_s' \tag{51}$$

where E_s' is the dynamic modulus of the soil, R_p' and R_s' are the elastic terms for the pavement and soil, and ϕ is a function developed by the theoretical analysis of layered systems (Henkelom and Klomp, 1962).

The vibrational responses of pavement structures to complex seismic waves has been applied to predicting actual pavement deflections under moving traffic. Theoretical mechanical models have been formulated containing such parameters as mass, stiffness and damping factors, which represent the pavement behavior (Szendre and Freeme, 1967).

The operation of two currently available vibratory systems, the Lane-Wells Dynaflect and the Shell Vibrator, were reviewed by the Texas Transportation Institute (Schrivner and Moore, 1968).

Use of the Dynaflect in obtaining relative measurements of pavement component strength has been reported (Schrivner and Moore, 1966). Relative rankings were obtained by observing the Dynaflect deflections for a wide variety of carefully constructed mats of varying layer thickness. The surface deflections were then related to the material properties by mathematical models which were based on the theory of elastic deformations for layered systems. Good agreement was obtained with other ranking methods but Schrivner and Moore concluded that, at that time, information provided by one set of Dynaflect readings was not sufficient to determine the relative stiffness of each layer.

Currently, devices such as the Dynaflect are most commonly used for quality control measurements during highway construction. Relative measurements may be readily obtained which yield ratings or evaluations of uniformity based on layer stiffness (Swift, 1966).

4.3.2 b. Plate-Load Tests

The use of plate-load tests would appear to be the most reliable and direct method of obtaining realistic strength values based on layer properties, since the magnitude of the applied load and extent of influence on the pavement system is similar to the actual vehicle loading conditions. However, numerous theoretical and field studies indicate that plate-load behavior is quite complex and the values obtained are of limited applicability unless consideration is given to understanding the nature of plate bearing behavior. Two layer systems will be considered in the discussion of the plate-load test. Multi-layer development and application will be discussed in Sec. 4.4.

The surface deflection, w, of a rigid plate on a two-layer system has been theoretically established as

$$w = \frac{1.18\ sr}{E_2} F_w \tag{52}$$

where s is the applied pressure in psi, r is the plate radius in inches, E_2 is the modulus of elasticity of the lower layer and F_w is a dimensionless constant which depends upon the ratio of the moduli of layer 1 and layer 2 as well as the ratio between the depth of layer 1 to the radius of the plate (Burmister, 1943). The above expression is valid for homogeneous, isotropic elastic solids which are continuous across the interface between the two layers. Burmister has published graphical relationships between E_1/E_2, h/er and F_w where h is the depth of the upper layer.

Various approaches have been used to apply the basic elastic expressions to plate load testing. Perhaps the simplest and most straightforward method is to perform a plate-load test on the subgrade, in which case the load-deflection relationship is

$$w = \frac{1.18\ s\ r}{E_2} \tag{53}$$

from either the Boussinesq or Burmister theory. E_2 may then be evaluated for the subgrade. In normal testing procedures the load, and hence s, is increased until a given deflection of normally 0.2 inches is obtained. Repeating the plate-load test on the surface results in the determination of a value for F_w from which the modulus of the upper layer may be determined (McLeod, 1963).

An alternate approach is to perform several plate-load tests on the pavement surface with varying sized plates. The load required to obtain a 0.2 inch deflection is graphically related to the radius of each plate used. A similar theoretical curve is then found by trial and error. A ratio E_1/E_2 and a value for E_2 are assumed, and with a known h/r ratio, a value of F_w is obtained which will produce a calculated load equal to the observed load. When correct values of E_2 and E_1/E_2 are selected, the theoretical and field curves will coincide (Brown, 1962).

The simple two layer theory has been extended to actual pavement structures by Brown. He assumed that the surface, base and subbase act as a single upper layer overlying the subgrade.

Another approach has been suggested in which two or more lower layers are considered to act compositely, resulting in a combined or effective modulus (McLeod, 1965). McLeod found that stepwise approximate applications of two layer theory to multi-layer conditions lead to relatively poor results even if all layer moduli are considered equal.

A recognized limitation of the plate-load test is that the plate's supporting power is related to the perimeter/area ratio of the plate itself. As this ratio decreased with increasing plate size the allowable pressure required to reach a specified deflection decreases (Campen and Smith, 1947). In addition, the rate of loading, the magnitude of the deflections obtained, the layer thicknesses and the material type all contribute to variations in moduli calculated by plate-load tests.

A large scale, cooperative field study of the application of plate load testing to pavement behavior was carried out in 1958 at Hybal Valley, Virginia (Benkelman and Williams, 1959). Initial analysis of the data confirmed the existing concept that the unit pressure, s, developed was expressed as

$$s = m \frac{P}{A'} + n \tag{54}$$

where m is the perimeter shear in lbs/in, n is the developed pressure in psi, P is the applied load and A' is the cross sectional area of the plate (Ingimarsson, 1961).

An extensive study of the Hybal Valley tests found a total of thirteen independent factors affecting the test results (Kondner and Krizek, 1961; 1966). The results of a dimensional analysis of the test results showed that hyperbolic equations could be used to explain the effects of temperature, repeated loadings plate size, pavement thickness and material strength.

A simple, straightforward approach was used by Oklahoma to evaluate the load supporting capacity of various layers within a pavement. The loads required to obtain various deflections of 0.03, 0.04 and 0.05 inches, were divided by the layer thickness. Each type of material was then ranked relative to a standard stabilized aggregate base course (Helmer, 1965).

A limited number of full size layer systems have been tested under repeated load contitions by plate-load methods (Seed, Mitry, Monismith and Chan, 1967). The cyclic plate-load tests were intended to obtain a more realistic appraisal of pavement behavior. One-, two- and three-layer systems were tested with various sized plates over several thousand applications of load. The resilient deformation of the surface and interfaces was continuously recorded. The method of analysis used to evaluate the data will be discussed in Section 4.4.2.

4.3.2 c. The Benkelman Beam

The Benkelman Beam is a simple, mechanical device used to measure pavement deflections under actual wheel load conditions. It was developed in 1953, and since that time has demonstrated its versatility as a research tool (Carey, 1953; Carneiro, 1966).

The Canadian Good Roads Association has made extensive use of the Benkelman Beam as a measurement of relative pavement strength and as a means of determining fluctuations of annual load carrying capacity (Sebastyan, 1960; Curtis and Shields, 1960). An extensive investigation into procedures, influencing factors and practical applications for the Benkelman Beam have been reported (Wilkins, 1962).

Deflection studies at the AASHO Road Test resulted in the mathematical model

$$d = 10^{a_o + a_1D_1 + a_2D_2 + a_3D_3 + a_4L_1} \qquad (55)$$

which relate the Benkelman Beam deflections, d, to the pavement layer thicknesses, where a_o to a_4 are strength coefficients for the respective layers and L_1 is the axle load.

The general form of the model was adopted by Virginia as

$$\log d = a_o + a_1 D_1 + a_2 D_2 + a_3 D_3 + a_s G_s \tag{56}$$

where a_s is a function of the soil strength and G_s is the equivalency grading of the subgrade soil support. With the exception of the subbase layer, the tests produced relative strength coefficients in good agreement with those recommended by the AASHO Committee (Vaswani, 1967).

Benkelman Beam tests have been used by the state of Minnesota in the development of a method for predicting allowable axle loads on existing highways during periods of spring thaw. A linear load-deflection relationship was assumed as

$$L_A = L_D \frac{d_a}{d_s} \tag{57}$$

where L_A is the allowable spring axle load, L_d is the axle load used for the tests, d_s is the predicted deflection based on the Benkelman Beam test and d_a is the allowable spring deflection based on theoretical pavement behavior (Kersten and Skok, 1968; Kruse and Skok, 1968).

An alternate use of the Benkelman Beam was mentioned in Sec. 3.4, where deflection measurements were directly related to performance expressions. The resulting terms were then related to initial pavement design and regional behavior.

Benkelman Beam measurements have been used to determine the modulus of elasticity of individual pavement layers (Walker, Yoder, Spencer and Lowry, 1962). This was accomplished by measuring the deflections at the interface of each pavement layer as well as on the pavement surface.

Correlations have been established between Benkelman Beam and plate-load test results (McLeod, 1965, Sebastyan, 1960). The load on a large rigid plate required to produce a specified deflection was converted to the load required to produce a deflection equal to that obtained from the Benkelman Beam test. Relationships between the composite Benkelman Beam and plate-load moduli were then established.

Recent studies have indicated a reasonable correlation exists between static Benkelman Beam deflections and dynamic deflections produced by the Lane-Wells Dynaflect. This has led to the conclusion that the vibratory system responds to the same physical properties of a flexible pavement structure which govern the behavior observed by the Benkelman Beam tests (Scrivner, Swift and Moore, 1966).

The desirability of measuring in-situ pavement deformations under full-scale loading conditions has led to the development of additional methods for evaluating deflections (Zube and Forsyth, 1966). Automatic recording optical and mechanical devices provide deflection measurements more rapidly and with greater precision than the conventional Benkelman Beam (Prandi, 1967).

4.4 Uses for Layered Elastic Theory

4.4.1 Background

Highway pavement systems are composed of layers of material constructed on a subgrade to form a structure capable of carrying traffic loads. The theory of elasticity, as applied to multi-layered systems has been extensively examined in an attempt to understand the complex load, stress, deformation relationships which occur in a pavement structure.

The theoretical behavior of one- and two-layer systems has been investigated by Westergaard, Boussinesq and Burmister (Westergaard, 1925; Boussinesq, 1855 and Burmister, 1943). The latter two theories have received the most consideration in the area of flexible pavements for it is felt they more accurately describe the actual behavior. Extensions of Burmister's work resulted in the evaluation of mathematical expressions and coefficients from which stress, strains and deflections could be obtained throughout a two layered system (Fox, 1948; Hank and Schrivner, 1948; Odemark, 1949). Use of the Westergaard theory has been suggested for predicting the stress distribution in asphalt pavements whose bases are rigid relative to the strength of the subgrade (Hagstrom, Chambers and Tons, 1965).

With the advent of the electronic computer, general expansion of layered theory was feasible (Acum and Fox, 1951; Peattie and Jones, 1962). Theoretical stresses and deflections were predictable within the upper layers and at layer interfaces for several material and continuity conditions.

Recently, multi-layer programs have been developed for general use which will describe the complete state of stress and strain within any part of a multi-layered system (Peutz, Jones and Van Kempen, 1968; Warren and Eieckmann, 1963). A great deal of emphasis is currently being placed on such solutions and how they relate to observed behavior. The determination of structural equivalencies and equivalent wheel loads, based on the elastic layer theory, stem from this research.

4.4.2 Verification of Elastic Behavior

Various investigations have tried to verify the elastic theory on laboratory and field bases. The behavior of circular, loaded plates resting on a uniform sand layer demonstrated that the vertical and radial stresses could not be predicted by the Boussinesq theory. The deflections measured under repeated-load conditions were better predicted by assuming a homogeneous, anisotropic, elastic material (Morgan and Holden, 1967).

Model tests on two-layered systems have been examined (McMahon and Yoder, 1960). In general, the observed stresses were only in fair agreement with those predicted by elastic theory. Field studies of three-layered systems indicate that the distribution of stresses in upper layers of material, such as soil cement or concrete stabilized bases, can best be approximated by the Burmister theory. The material's ability to carry tensile stresses accounts, in part, for this agreement. The Boussinesq stress distribution appears more applicable for untreated granular and asphaltic materials (Vesic, 1962).

The surface deflections observed by repeat-load plate-load tests on several multi-layer systems have been predicted with good agreement by using multi-layer analysis (Seed, Mitry, Monismith and Chan, 1967). An extensive series of laboratory repeated-load triaxial tests were performed to determine how various factors affected the resilient modulus. The large-scale system was then examined, using the Boussinesq theory, to determine the confining pressure at various points throughout each layer. Appropriate laboratory moduli were selected on the basis of the number of load cycles and conditions of confining pressure. The predicted deflections were based on the summation of individual deflections calculated from each incremental division for the entire structure.

4.4.3 Predicting Material Equivalencies

The behavior of three-layer pavement systems, based on assumed models, has been used as a means of developing theoretical design methods (Dorman and Metcalf, 1965). The elastic properties of the three layers, the loading conditions and the number of repetitions were defined. Design criteria were selected as limiting values of vertical compressive strain in the subgrade and tensile strain within the asphalt layer. The individual depth of surface and base required to maintain acceptable limits of strain were plotted graphically against one another. This allowed all alternate designs to be shown graphically. The equivalency ratio between the surface and base for any suitable combinations of either material was also obtained.

A similar three-layer investigation was performed using an assumed pavement model with a specified loading condition. Laboratory determined values of the complex moduli for each layer were used. Allowances were made for the frequency of the load and the temperature distribution and fluctuation within the pavement. Theoretical equivalency ratios were established for the base material by calculating the required amount of base needed to compensate for decreasing the surface thickness one inch while maintaining constant surface deflections (Coffman, Ilves and Edwards, 1968).

4.5 Factors Relating to the Structural Coefficients

The use of structural coefficients greatly enhances the AASHO Design procedure for they allow various combinations of acceptable designs to be readily examined. However, the concept of structural coefficient has several serious shortcomings.

As indicated in Sec. 4.2, the practical evaluation of the coefficient values by standard tests is not possible either for materials used at the AASHO Road Test or for other types of materials used elsewhere. For this reason, equivalent strength ratings are frequently used to measure the effectiveness of road building materials.

The difficulty in establishing these values is twofold. There are serious doubts as to whether the standard material tests accurately describe in-situ behavior. Secondly, complex and extensive testing programs, both on a theoretical and experimental basis, demonstrate that the behavior of pavement material cannot, at present, be adequately described. Young's modulus, E, and Poisson's ratio, μ, govern the behavior of elastic solids. Under actual test conditions, both values have been found to vary with the factors given in Sec. 4.3.1 a.

The behavior of a layered system, and hence the resulting equivalency ratios vary with the basic boundary and continuity conditions, the criteria established for equivalency and the relative position, strength and thickness of each layer. Thus it appears that, at best, equivalency ratios and structural coefficients are variable. A more accurate picture of the possible range of these coefficients should be established for all adverse conditions which are normally obtained under conventional loading and environmental conditions. In addition, further research is needed to theoretically account for the non-ideality of pavement systems.

A recently completed study has considered the consequences of using incorrect structural numbers when predicting pavement life by the AASHO design method (McCullough and Van Til, 1968). The general AASHO flexible pavement formula was differentiated with respect to the structural number, and percent errors introduced in that term to determine the variation in the calculated number of wheel loads. Overestimating the structural number was found to be far more serious that underestimating it. The amount of error increased with decreasing structural numbers. The effect of relatively small errors, such as 5 percent, may lead to overestimating the design life of a typical section by 100 percent. The significance of such findings justifies current research into the behavior of materials and pavements.

V. SUBGRADE SOIL SUPPORT

5.1 Soil Support in the AASHO Design Method

The concept of a subgrade soil support term was advanced by the AASHO Committee so that the design method developed from the Road Test results could be extended to geographic areas which have soil characteristics different to those at the test site. The assumed relationship between soil support and number of axle loads, and its incorporation into the design method, are given in Chapter II. Hence, a soil support value must be either assumed or determined for a proposed roadbed prior to using the design charts, (see Fig. 2).

The fundamental problems are involved in the soil support concept. First, there is no basic physical relationship between the soil support term and currently used testing methods. Secondly, there are no rational or definite experimental methods for establishing valid correlations between any standard testing procedures and the soil support term.

5.2 Correlation Studies

Despite the fact that no standard, universally accepted correlation methods are available, several such scales have been proposed by the AASHO Design Committee (HRB Special Report 73, 1962). An extensive research program was carried out at the Road Test in order to determine the subgrade soil properties by the best available methods. In addition, samples of the soil were tested by a large number of agencies throughout the country (Skok and Fang, 1961). The results of the site tests, and that done by other groups, served as a basis for the correlation studies. The AASHO correlation charts were based on

1. R-value (California)
2. R-value (Washington)
3. CBR (Kentucky)
4. CBR (Kentucky, for bituminous bases)
5. Group Index

As shown in Fig. 3, the R-value and Group Index scales are linear and the CBR scales are logarithmic.

Several similar correlation studies have been performed since the Road Test. Laboratory tests performed by the state of Illinois on the AASHO A-6 subgrade soil and crushed aggregate base course resulted in CBR values of 3 and 110 respectively. The soil support values of 3 and 10 were replaced by the Illinois CBR values, and a logarithmic distribution assumed for intermediate values (Chastain and Schwartz, 1965).

Utah conducted a number of laboratory tests in order to determine the repeatability of four test methods: the AASHO 3 Point CBR, Static CBR, Dynamic CBR and R-Value. A logarithmic correlation scale between soil support and Dynamic CBR was assumed. The other three tests were tied into the soil support scale by equating their results to those from the Dynamic CBR tests (Sorbe, 1967). Graphical relationships between the soil support term and results from each test were established for design purposes.

The state of Massachusetts formulated a similar correlation scale between CBR and soil support (Tons, Chambers and Kamin, 1965). A literature survey of available information covering support values for the compaction methods desired by Massachusetts resulted in selecting bearing values of 5.5 and 100 as representing soil support terms of 3 and 10, respectively. A logarithmic distribution was assumed between the two points.

A correlation scale for Georgia soil was developed after an evaluation of the entire pavement structure. Undisturbed cores obtained from pavement sites, as well as several from the AASHO Road Test, were subjected to undrained triaxial tests with varying conditions of lateral pressure. Simplified expressions for the elastic deformation and ultimate bearing behavior of the roadbed were assumed. Relationships between loadings, pavement design and factor of safety against subgrade bearing failure were established for both AASHO and Georgia conditions. A logarithmic scale was then proposed which related computed ultimate bearing capacity, based on triaxial tests, and subgrade soil support values (Sowers, 1965).

The use of undrained triaxial tests was also proposed by South Carolina as a means of finding the subgrade support of the roadbed at sixteen sites (Chu, Humphries and Fletcher, 1966). The tests were conducted on disturbed specimens whose density and water content equaled those which were assumed to exist during construction. Samples 4 in. in diameter and 8 in. high were subjected to lateral pressures comparable to those existing under 18^k loading conditions in the field and the modulus of deformation of the soil determined. The results of additional tests on AASHO embankment and granular base material, both by South Carolina and others, served as a basis for a correlation between the soil support term and the logarithm of the modulus of deformation.

A recent theoretical study has developed a correlation scale relating soil support values to resilient moduli (McCullough and Van Til, 1968). An elastic, multi-layer model was chosen to represent the behavioral characteristics of a highway pavement. A literature survey indicated that subgrade moduli on the order of 3000 psi for a clay roadbed and 15,000 to 35,000 psi for a crushed stone base would describe the two predetermined soil support conditions at the AASHO test site. Various values of thicknesses and elastic moduli of the surface were selected to cover the ranges normally encountered in practice. Standard dual wheel, 18 kip axle loads served as a basis for the assumed model load. Vertical compressive strains in the subgrade and tensile strains in the bottom fibers of the asphalt surface were calculated. These values were related to the weighted number of load applications obtained from the standard AASHO design equation. The evaluation of the trends between number of applications and derived strain resulted in a logarithmic scale between soil support and resilient moduli values.

5.3 Significance of the Soil Support Term

The structural behavior of a subgrade is reflected by the material's in-situ properties. These vary according to the items mentioned in Sec. 4.3.1 and 4.3.2. Elastic layer analysis has indicated that subgrade compressive strains are a critical design criteria for typical pavements (Dorman and Metcalf, 1965). It has been tentatively concluded that as the stress on a layered system increases, the modulus of the base increases while that of the subgrade decreases. The resulting resilient deformations in the subgrade therefore become more critical (Seed, Mitry, Monismith and Chan, 1967). Thus knowledge of the behavior of the subgrade is important and the magnitude and variation of the subgrade's properties contribute to the overall behavior of the structure.

A significance study indicated that, similar to the structural number, small errors in the assumed values of soil support lead to large errors between the actual and calculated number of load applications as determined by the AASHO design method (McCullough and Van Til, 1968). As with the structural number, underdesign resulting from overestimating the soil support value results in more significant errors than if conservative values were selected.

At present, correlation charts are the only practical means of relating soil properties to the soil support values required by the AASHO design. However, further research is required to adequately demonstrate that these methods actually evaluate in-situ behavior.

VI. TRAFFIC

6.1 Background

The behavior of the AASHO Road Test pavements were evaluated under a definite, controlled loading program. Each series of related sections, or loops, were subjected to axle loads of known magnitude, configuration and frequency in such a manner that the effects of very light to very heavy loads could be observed. The analysis of the performance data, as summarized in Chapter II, was based on the relationships between structural design, change in serviceability and accumulated 18 kip axle loads. The equivalent axle concept allowed various types of loads to be reduced to a common or equivalent number of repetitions in order to simplify the analysis and resulting use of the test data. Thus, based on the resulting Road Test equations, it was possible to predict the total number of applications of load which would reduce a given highway, of known design, roadbed and environment, to a specified level of serviceability.

For convenience, an arbitrary design life of 20 years was selected, and the total applications were reduced to the more conventionally accepted form of daily equivalent applications. Hence, the AASHO design method, as summarized by Fig. 2, requires a value for the equivalent daily 18 kip single axle load applications.

6.2 The Equivalent Applications Concept

The AASHO Road Test loadings were very limited when contrasted to the wide range of vehicle size, type and speed normally encountered under actual situations. The conversion of mixed traffic into forms related to the AASHO conditions can be expressed by either mixed traffic or equivalent applications theory (Scrivner and Duzan, 1962).

The mixed traffic method provides an approach for summing the results of individual weight classes based on representative samples. The relationships between deterioration, serviceability index, application, load and design from the AASHO Road Test data were applied to each weight class in a manner which allowed the summation of all repetitions in each class to be evaluated. However, the resulting mixed traffic theory formulas were in forms impractical for general application.

The equivalent applications theory is based on the concept that if one load is selected as a standard, the effects of both lesser and heavier loads may be referenced to it by ratios which reflect equivalent, long term behavior. The basic AASHO equations provided a means for accomplishing this. Equation 4 may be rewritten as

$$W_a = \rho_a \, G^{1/\beta_a} \qquad (58)$$

where one axle load type was denoted by the subscript "a". An equivalency ratio, or factor, between this weight class and another, denoted as "i", was then established as

$$R_i' = \frac{W_a}{W_i} = \frac{\rho_a \, G^{1/\beta_a}}{\rho_i \, G^{1/\beta_i}} \tag{59}$$

The factor, R_i', was a function of the structural number, axle configuration and terminal serviceability. Equivalency factors have been based on the 18 kip single axle load and tabulated for design purposes (HRB Special Report 73, Appendix B, 1962).

6.3 Uses of the Equivalent Applications Concept

Many factors enter into the practical conversion of mixed traffic to equivalent axle loads. Foremost among these are establishing methods to count and weigh samples of existing vehicles in order to determine current traffic characteristics. Secondly, methods of projecting traffic information over the expected design life of the roadway are necessary. In many instances simplified projection factors are used, but a complete growth rate analysis is very complex and involves many factors, a discussion of which is beyond the scope of this report.

The basic requirements for a fundamental traffic analysis have been set forth in the Satellite Study Guidelines (Irich and Hudson, 1964). A complete description of the traffic over a pavement section requires parameters which must be approximated by sampling techniques to obtain a representative traffic history. Several fundamental steps will be given to develop the basic approach used in traffic studies.

All possible types of vehicles are broken down into axle load categories which are normally divided into 2 kip increments. Loadometer or vehicle load studies then weigh vehicles passing a specified section over a predetermined period, such as 24 hours. In general, only trucks and other heavy commercial vehicles are weighed due to the basic similarity of automobile weights. The total number of equivalent axle loads is then the summation of the number of equivalent loads in each weight class, as converted by using the appropriate factor.

Since loadometer studies are costly and time consuming, traffic counts are commonly used to supplement this information. Traffic is divided into broad, readily identifiable classes and the number in each class passing a particular point is counted. The percent within each class is then used to extrapolate the loadometer information. The daily load and count studies are then either developed to establish a traffic history or extended to estimate future volume. Counting and load studies are required often enough to obtain an accurate picture of the trends and fluxuations in a particular area.

A recent study has indicated that nine indpendent variables commonly affect traffic flow at a specific site (Deacon and Dean, 1969). These include road type and direction, availability of alternate routes, type of service provided, traffic volume, allowable gross weights, geographic area, year and season. Determining methods to encompass and correlate the variables has proven difficult. The significance of these items is twofold. First, the study indicated that traffic data observed at one location may not readily be extended to another without very careful consideration of the factors involved. Secondly, changes or trends in any one of the variables may invalidate traffic predictions established for a given roadway.

6.4 Traffic Data

The reduction and use of traffic data is handled differently by many states due to many differences in the nature of traffic, basic needs, past data collected and availability of funds. The approaches used by several states for satellite studies or design practices will be discussed briefly.

Loadometer data which reflected conditions surroundings a portion of the Road Test sections were available for use in Alabama. This information allowed graphical relationships between average daily traffic, ADT, and anticipated equivalent axle loads to be developed and used to estimate the traffic history at each site (Karrh and Stephenson, 1967). Visual classification of traffic into several broad categories was carried out at each site not covered by existing data. Approximate equivalent 18^k applications were then obtained from the count and estimated weight survey by the procedures recommended in the AASHO design method.

Count surveys for the type and amount of each vehicle were available during the Virginia study. The conversion of this information to 18 kip equivalent wheel loads was based on values established at loadometer stations with similar traffic conditions. The equivalency factors presented in 1966 by the Bureau of Public Road's Truck Weight Study were used in preference to those originally recommended by the AASHO Design Committee (Vaswani, 1967).

An extensive traffic analysis was associated with the Minnesota satellite study program in order to evaluate the total 18 kip EAL's applied to the test sections. Methods for projecting the traffic data based on satellite trends were formulated. The study concluded that the state should convert from basing design on average daily commercial traffic to the equivalent applications approach. The study also pointed out the significance of seasonal variation in the number of heavy commercial vehicles and concluded that traffic load studies should be conducted over several periods spaced throughout the year (Kersten and Skok, 1968).

Loadometer data from 19 stations throughout Illinois was used to formulate axle load distributions which were considered applicable to the entire rural primary system in the state (Chastain, 1962). Based on many years of collected traffic data, general projected graphical relationships were formed between 18^k EAL's per 100 commercial vehicles and any specific year. This allowed the total equivalent applications to be determined from truck counts. The effects of passenger cars was determined independently on the basis of a normal 4000 lb. vehicle.

The state of Massachusetts has broken its traffic data into weight classifications other than those established by the AASHO method. This required that revised equivalency factors be calculated in terms of the previously defined weight classes (Tons, Chambers and Kamin, 1965).

A recent study of the AASHO design method summarized several basic traffic analysis methods currently in use (McCullough and Van Til, 1968). Variations between methods are basically due to how many vehicle weight divisions are selected and how the information obtained by traffic counts and loadometer studies is related and projected. Differences in number of traffic classifications and methods used to project the data, reflect the many different systems for handling traffic. The survey concluded that the loadometer data reduced by the BPR's W4 tables was the best available method.

6.5 Further Research Requirements

The equivalent applications concept, obtained from the Road Test findings, serve as basis for incorporating traffic data into the AASHO design method. Revisions by the BPR in the actual values of the equivalency factors are felt by some to be more accurate than the originally recommended values. Theoretical studies, using elastic layer theory, are currently being considered for finding load equivalencies (Huang, 1969). These are, at present, limited, for only the effects of design, single wheel load and critical strains and deformations are considered.

The limitations of the equivalent wheel load concept should be recognized. It is the result of a statistical study of a relatively restricted highway test. The complete description of actual mixed traffic is very complex due to the effects of variations in speed, axle configuration and load, and the long term relationship between loads and pavement system behavior.

The need for more accurate traffic information has been recognized by many researchers since the development of the Road Test. Irick pointed out that existing techniques in traffic counting were adequate but loadometer information, in general, was inadequate for the AASHO design method. The same general conclusion has been advanced by McCullough. In addition, it is possible to obtain a wide range of results from the same fundamental data by using various existing traffic projection methods currently available. It is pointed out that this may not be significant within a state which, through its own experience, has probably learned to inherently compensate in other steps in the design method. However, the general use of incomplete or simplified methods is not advised for it can lead to serious errors.

VII. REGIONAL FACTOR

7.1 Philosophy

A regional factor was incorporated into the AASHO design method to account for environmental influences on the behavior of a highway. The assumed relationship between regional effects and pavement life, and its inclusion into the general AASHO design formula, is given in Chapter II, (see Fig. 2).

It was recognized that no rational procedure was available to evaluate the regional factor for the variety of conditions present throughout the country. However, guidelines and suggested values were proposed by the Design Committee (Langsner, Huff and Liddle, 1962).

Following the Road Test, evaluation of regional factors was to be accomplished through satellite study programs. The tentative procedure was to observe the behavior of many similar pavements with similar loading conditions which were located in different environments. The regional factor would then explain differences in test data not covered by the structural and soil support terms. Furthermore, determining the properties of one section with characteristics similar to those at the Road Test would allow correlations to be made with the original regional factor scale. A list of climatic and topographic variables, such as precipitation, frost, drainage and grade, have been recommended by the Guidelines as being areas of potential interest for individual states (Irick and Hudson, 1964).

7.2 Environment-Evaluation by States

Various states have attempted to experimentally evaluate regional conditions for their own specific locale. These have generally been carried as part of a total assessment and study of the AASHO design method.

A performance study in Alabama suggested that the behavior of a wide variety of sites could be better explained by dividing the state into several geographic regions. However, it was concluded that regional factors required to explain the variations in pavement behavior were excessively large and that the effects of climate and construction techniques, as related to the structural design, could not be explained in terms of the basic AASHO equations (Karrh and Stephenson, 1967).

Minnesota completed an extensive study of year-round pavement behavior to determine a means of evaluating the effects of seasonal variations. It was found that an average variation of 152 percent existed between maximum (or springtime) and fall Benkelman Beam deflections (Kersten and Skok, 1968). This information was used to develop a design procedure for specifying allowable spring tonnages on Minnesota's highways. No work was directed towards developing an AASHO regional factor but further research into the general area of environmental effects was recommended.

Illinois found that the direct application of the AASHO formulas did not correctly express the deterioration of serviceability for its highways. However, the formulas did follow observed trends if somewhat weaker structural designs were assumed. The use of a time exposure factor was proposed which would alter the Road Test results to fit the observed performance (Chastain, 1962). The factor, T, was defined as

$$T = {}^{D_t}/_{SN} \tag{60}$$

where D_t = the Illinois structural number in the form of Eq. (10). This factor was to account for the long-term deterioration of pavements due to environmental effects. Subsequent studies indicated a value of T = 1.10 could be used for design purposes (Chastain and Schwartz, 1965).

A study of the regional influences on pavement behavior has been carried out in Texas to evaluate the factor, C_r, as given by Eq. (40) (Schrivner and Moore, 1966). A series of Dynaflect tests were taken on 188 flexible sections throughout the state and the results correlated with those observed at the TTI Pavement Test Facility. Three regions of equivalent pavement behavior and corresponding design values of C_r were proposed. A continuation of this study divided the state into five regions and revised the regional factors (Schrivner and Moore, 1968). Although these values are applicable to the Texas design method, their relationship to the regional factor, R, was not given.

A blanket 15 percent increase in calculated structural requirements for use in Massachusetts highways was proposed due to frost problems, construction techniques, material differences and long term effects (Tons, Chambers and Kamin, 1965). The increase, which is comparable to a regional factor of 3, was based primarily on judgement and experience. Further research into regional problems was proposed.

Studies into general environmental conditions and/or regional factor determinations were proposed by the satellite projects in Georgia, Virginia, South Carolina and Oklahoma.

7.3 The Significance of Regional Factors

A great deal of field and laboratory research has been carried out relating the effects of frost action, moisture content and temperature effects (Haley, 1963; Jumikis, 1967). The significance of environmental conditions on basic material strength was discussed in Chapter IV and V. However, judging by the results of recently completed projects, there has been very little progress in the development of specific regional factors.

A recent study, examining various aspects of the AASHO design method, revealed that misuse of the regional factor can lead to serious over or under design (McCullough and Van Til, 1968). The error between actual and anticipated road life increases rapidly with decreasing values of the regional factor. The study also pointed out that many methods currently used for estimating the required factors are based on the conditions as rainfall, frost depth, elevation, drainage and temperatures. In general, the development of these values relies chiefly on experience and judgement.

The concept of the regional factor is the least advanced and perhaps the most difficult to ultimately establish. Much further study will be necessary before environmental factors can be explained or reduced to the simple terms of the AASHO design scale.

VIII. SUMMARY

The development of the fundamental AASHO design equations express the underlying concepts of structural design, soil support, accumulated axle loads and regional effects. Basic understanding of the framework and inherent limitations of the analysis is required before the method can be applied with any degree of success.

The AASHO performance equations, and those resulting from additional research, emphasize the importance of the performance criteria as a means of evaluating the suitability of a highway. The use of mathematical models describing deterioration have lead to techniques for predicting pavement life, assessing material strength and understanding composite behavior. The need for better serviceability measuring devices is currently receiving much attention.

The evaluation of material strength is of primary importance to researchers and highway engineers. Values of the structural coefficients for various surface, base and subbase materials resulted from the statistical analysis of the data observed at the Road Test. It was the intent of the Design Committee that subsequent work, mainly by state satellite study programs, would develop testing methods to verify the existing values and find new ones for material used elsewhere. Correlation studies using relatively standard testing techniques have only partially satisfied this demand.

Since currently employed conventional testing methods generally examine only one limited strength parameter and are applicable to one type of material, much emphasis has been placed on developing laboratory and field tests which more closely approximate the in-situ conditions. The purpose of such tests is to determine the equivalent strength of a variety of material types under realistic loading conditions. Equivalencies based on different types of dynamic moduli obtained from repeated-load or seismic tests are under current examination.

The need for a better rational approach to pavement behavior has lead to extensive examination and use of multi-layer, elastic solutions. Although not altogether successful, combined field, laboratory and theoretical studies have greatly increased the understanding of significant interrelationships between the many factors involved in pavement behavior.

The support properties of the roadbed have to be expressed in terms of the AASHO soil support factor. Various standard testing techniques, such as R-value or triaxial tests, have been used to formulate correlation charts. Interestingly enough, no significant developments have been made in using field testing techniques to evaluate the soil support factor.

The AASHO design method is based on prior knowledge of the loading conditions over the life of the highway. Furthermore, the estimated mixed traffic must be reduced to standard 18 kip equivalent axle loads by traffic equivalency factors. The number and distribution of various types of traffic is found by count and loadometer studies. This information may be reduced and projected over the design life by a number of currently available methods.

Guidelines were suggested by the Design Committee for specifying the regional factor based on general environmental conditions. It was originally intended that this factor could best be defined by individual studies in each state. As a whole, although most states understand their particular environmental problems and compensate for them in design methods, little success has been met in developing a rational method for finding the AASHO regional factor.

IX. CONCLUSION

The AASHO design method, either in part or in total, has received widespread acceptance throughout the country. The rapid acceptance and adoption of the design method pointed out the need for a comprehensive national road test research program whose magnitude exceeded anything which could be accomplished by individual states. The AASHO Road Test has perhaps been the most significant single event in the history of roadbuilding for it offered, in addition to the design method, opportunities to explore new methods of analysis and to develop new equipment and testing techniques. Further, the Road Test has served as the chief stimulus for highway research over the past decade.

However, the AASHO design method does have serious drawbacks and limitations, many of which lie within the fundamental approach, scope and analysis of the results. Pavement behavior was established primarily on a statistical basis. As a consequence, terms such as the structural coefficients have no direct physical or rational basis and cannot be reproduced, or even correlated completely successfully, with existing methods. In addition, the Road Test was conducted in one environment and on one roadbed. The necessary elements of soil support and regional factor were only indirectly evaluated in terms of arbitrary mathematical models. As with the structural coefficients, the soil support and regional factors do not readily lend themselves to rational analysis and experimental evaluation.

Although important advancements have been made, especially in the area of material strength, no one satellite study program has successfully covered each aspect of the design method. More significantly, several states which are most active in highway research, such as Texas and California, have not adopted the design method.

A recent study of current practice pointed out that many states use the AASHO method without modification, and develop the necessary terms mainly on the basis of experience and judgement (McCullough and Van Til, 1968). The serious ramifications of errors in any one of the required variables have been demonstrated by the study.

Current literature indicates a trend towards more fundamental research in basic material behavior. At present, factors which govern the strength of individual types of materials are not fully understood. Furthermore, theoretical, field and laboratory tests have all clearly established the highly complex nature of the soil-pavement system. Additional problems, such as environmental influences, long term loading conditions and the effects of mixed traffic, require much further study.

The use of theoretical multiple layer, elastic solutions has shown promise as a means of finding significant trends in behavior. Ultimately, material properties may be defined well enough and the existing theories modified to the extent that actual pavement behavior may be rationally defined.

The satellite study programs and parallel research have contributed greatly to the understanding of highways, but have as yet failed to establish the necessary testing techniques and methods of analysis required for a satisfactory evaluation of the variables required by the AASHO design method.

X. FIGURES

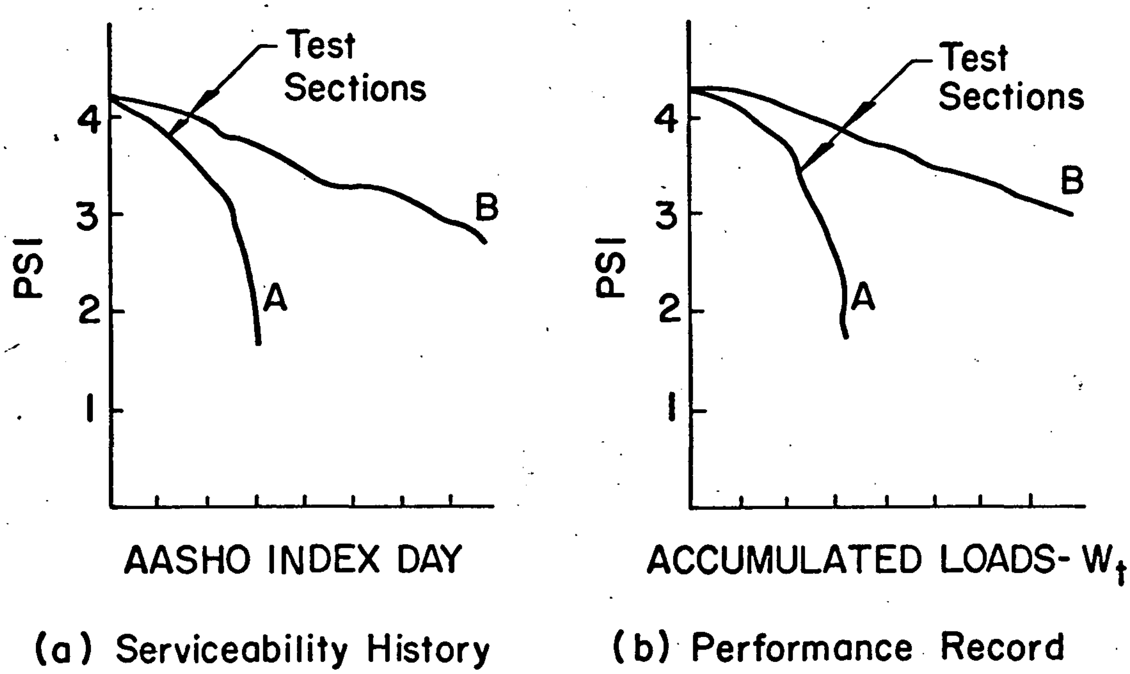

Fig. 1 Graphical Expressions of Performance

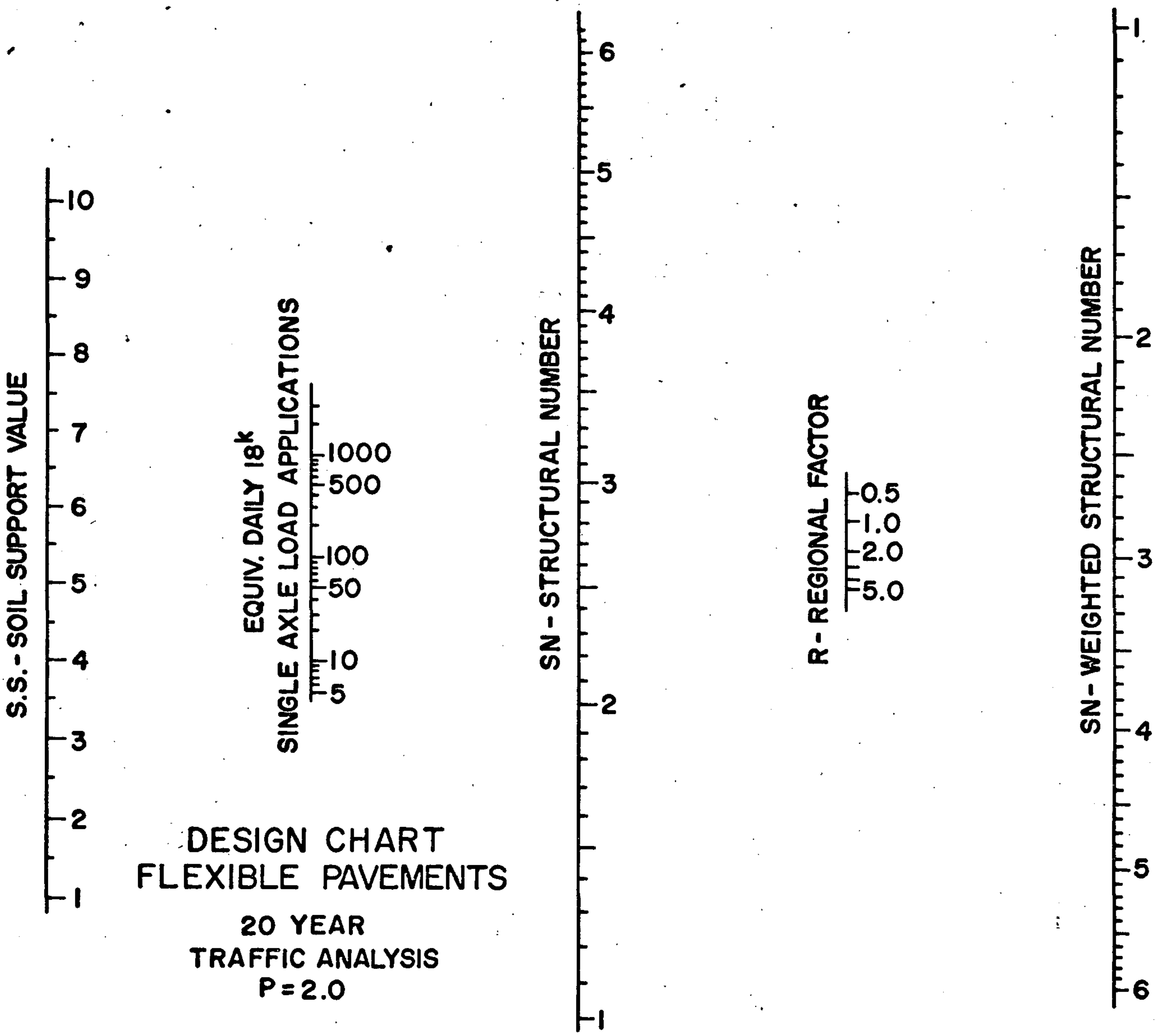

Fig. 2 AASHO Design Chart

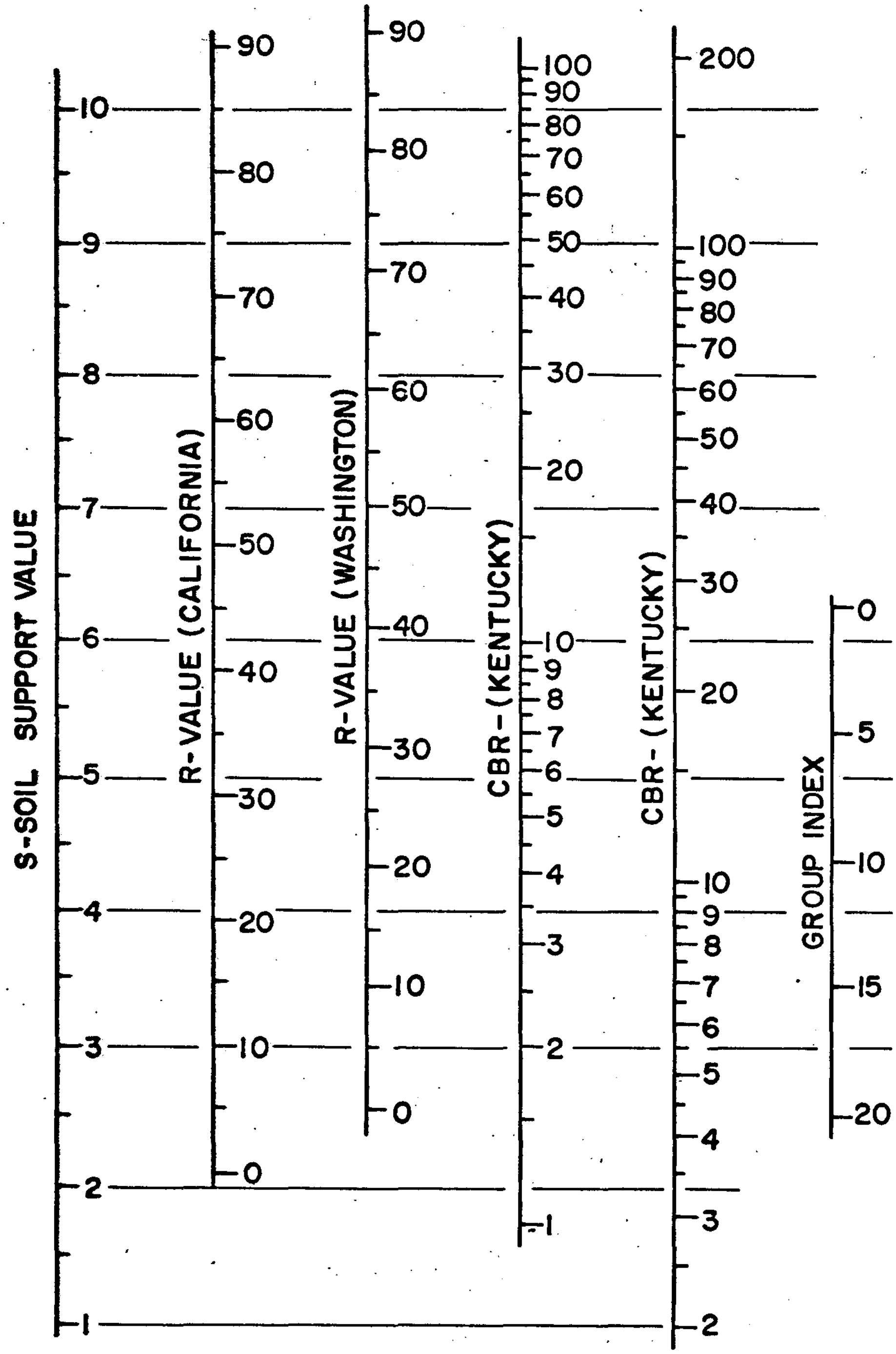

Fig. 3 AASHO Correlation Scale for Soil Support Values

XI. TABLES

DEVICE	REFERENCE
AASHO Slope Profilometer	HRB Special Report 61E, 1962
CHLOE Profilometer	Carey, Huckins and Leathers, 1962
BPR Roughometer	Yoder and Milhous, 1964
Minnesota Roughometer	Kersten and Skok, 1968
PCA Roadmeter	Brokaw, 1967
Kentucky Accelerometer	Rizenbergs, 1961
General Motors Profilometer	Spangler and Kelly, 1965
Univ. of Michigan Profilometer	Housel, 1962
Purdue Tire Pressure Measurement Device	Wilson, 1964
Mays Road Meter	Phillips and Swift, 1969
Texas Texture Meter	Scrivner and Hudson, 1964

Table 1. Devices Related to Performance Determinations

COEFFICIENTS[1] OF PAVEMENT COMPONENTS

Pavement Component	a_1	a_2	a_3
Surface course:			
Roadmix (low stability)	0.20		
Plantmix (high stability)	0.44*		
Sand asphalt	0.40		
Base course:			
Sandy gravel		0.07[2]	
Crushed stone		0.14*	
Cement treated (no-soil-cement):			
650 psi or more[3]		0.23[2]	
400 psi to 650 psi		0.20	
400 psi or less		0.15	
Bituminous treated:			
Coarse graded		0.34[2]	
Sand asphalt		0.30	
Lime treated		0.15—0.30	
Subbase:			
Sandy gravel			0.11*
Sand or sandy-clay			0.05—0.10

[1]It is expected that each State will study these coefficients and make such changes as their experience indicates necessary.

[2]This value has been estimated from AASHO Road Test data, but not to the accuracy of those factors marked with an asterisk.

[3]Compressive strength at 7 days.

TABLE 2. Proposed AASHO Structural Coefficients

XII. NOMENCLATURE

A, A_o'	Intercepts of linear plot
A'	Cross sectional area of plate
A_o, A_1, A_2, A_3	Mathematical constants
A_1	Slope of linear plot
A_o'', A_1''	Mathematical constants
B	Slope of linear plot
B'	Mathematical constant
B_1'	Slope of a performance index equation
B_o, B_1, B_2, B_3	Mathematical constants
C_R	Regional coefficient
D	Structural design term
D_1, D_2, D_3	Layer thickness of surface, base and subbase
D_t	Illinois structural number
E	Dynamic modulus of elasticity
E_s	Dynamic stiffness modulus
E_s'	Dynamic modulus of soil
E_1	Modulus of elasticity of layer 1
E_2	Modulus of elasticity of layer 2
$\|E^*\|$	Complex modulus
F	Applied dynamic force
F_w	Dimensionless constant
G	Logarithmic expression of serviceability terms
G_s	Equivalency grading

I	Moment of inertia
K	AASHO design formula term
K', K'', K''', K_o	Proportionality constants
L_1	Nominal axle load
L_2	Axle code
L'	Axle load and configuration term
L_A	Allowable spring axle load
L_d	Axle load used for test
M_R	Modulus of resilient deformation
N, N'	Material constants
P	Applied load on plate
PSI	Present serviceability index
Q	Performance expression in terms of 18^k EAL
Q_L	Performance expression
R	Regional factor
R'	Elastic stiffness
R_i	Axle load equivalency ratio
S	Measure of composite strength
SS, SS_i, SS_o	Soil support
SN	Structural number
S_1, S_2, S_3	Strength coefficients
S'	Dynamic stiffness expression
T	Time exposure factor
TDI	Texas Design Index
V	Wave velcoity
W_t	Accumulated axle loads at time = t
$W_{18}, W'_{18}, W''_{18}$	Accumulated 18^k axle loads at time = t

W_t^*	Accumulated axle load term
X	Observed value of log W_t
$\overline{X}$	Average of observed values of X
Y	Observed value of log log $^{P_o}/_{P_t}$
$\overline{Y}$	Average of observed values of Y
Z	Pavement displacement
a	Specimen dimension
a'	Elastic property of roadbed
a_1, a_2, a_3	Structural coefficients
a_4	Subgrade strength coefficient
a_1', a_2', a_3'	Structural coefficients
a_4'	Subgrade strength coefficient
a_o'	Mathematical term
a_s	Function of subgrade strength
b, b', b'', b_o	Deterioration rate parameters
d	Benkelman Beam deflection
d'	Observed deflection
d_a	Allowable spring Benkelman Beam deflection
d_s	Predicted Benkelman Beam deflection
h	Depth of upper layer
l	Specimen length
m	Plate-load perimeter shear
n	Developed plate-load pressure
p_o	Initial serviceability index
p_t	Present serviceability index
p_1	Terminal serviceability index
q	Elastic property of a roadbed

r	Radius of plate
r_1, r_2, r_3, r_4	Ratios of relative material strength
r'	Mathematical term
s	Applied plate-load pressure
w	Surface deflection from plate-load test
β, β_o	AASHO design formula terms
γ	Density
ε_o	Vertical strain
ε_r	Recoverable axial strain
θ	Sum of vertical and lateral stresses
μ	Poisson's ratio
ρ	Terminal number of axle load applications
σ_o, σ_1	Applied vertical stresses
σ_2, σ_3	Lateral confining stresses
σ_d	Repeated deviator stress
ϕ	Function relating seismic expressions

XIII. REFERENCES

Acum, W. E. A. and Fox, L. (1951), "Computation of load stresses in a three-layer elastic system", Geotechnique, Vol. 2, No. 4, pp. 293-300.

Benkelman, A. C. and Williams, S. (1959), "A cooperative study of structural design of non-rigid pavements", HRB Special Report No. 46.

Benkelman, A. C. and Carey, W. N., Jr. (1962), "Prediction of flexible pavement performance from deflection measurements", Proc. St. Louis Conference, HRB Special Report No. 73, pp. 224-226.

Boussinesq, J. V. (1855), Application des potentiels a' l'étude de l'équilibre et du mouvement des solides élastiques, Paris, Gauthier-Villars.

Brokaw, M. P. (1967), "A rapid measure of measuring slope variance", Highway Research Record No. 189, pp. 137-149.

Brown, P. P. (1962), "Analysis of flexible airfield pavements by surface plate-loading", Proc. International Conference on Structural Design of Asphalt Pavements, University of Michigan, pp. 37-42.

Burmister, D. M. (1943), "The theory of stresses and displacements in layered systems and applications to the design of airport runways", Proc. HRB, Vol. 23, pp. 126-149.

Campen, W. H. and Smith, J. R. (1947), "Use of load tests in the design of flexible pavements", Special Technical Publication No. 79, ASTM, pp. 51-64.

Carey, W. N., Jr. (1953), "Benkelman Beam deflection indicator, Highway Research Asbtracts, Vol. 23, No. 8.

Carey, W. N., Jr. and Irick, P. E. (1960), "The pavement serviceability - performance concept", HRB Bulletin 250, pp. 40-58.

Carey, W. N., Jr., Huckins, H. C. and Leathers, R. C. (1962), "Slope variance as a measure of roughness and the CHLOE profilometer", Proc. St. Louis Conference, HRB Special Report No. 73, pp. 126-137.

Carneiro, F. B. L. (1966), "Benkelman Beam - auxiliary instrument of the maintenance engineer", Highway Research Record No. 129, pp. 28-52.

Chastain, W. E., Sr. (1962), "Application of Road Test formulas in structural design of pavements", Proc. St. Louis Conference, HRB Special Report No. 73, pp. 299-313.

Chastain, W. E., Sr. and Schwartz, D. R. (1965), "AASHO Road Test equations applied to the design of bituminous pavements in Illinois", Highway Research Record No. 90, pp. 3-25.

Chu, T. Y., Humphries, W. K. and Fletcher, O. S. (1966), "Application of AASHO Road Test findings to the design of flexible pavement structures in South Carolina, Highway Research Record No. 131, pp. 87-106.

Coffman, B. S., Ilves, G. and Edwards, W. (1968), "Theoretical asphalt concrete equivalencies", Highway Research Record No. 239, pp. 95-119.

Curtis, W. E. and Shields, B. P. (1960), "Determination of spring load carrying capacity from Benkelman Beam deflections", Symposium on Pavement Design and Evaluation, Proc. 41st Convention CGRA, pp. 71-87.

Deacon, J. A. and Deen, R. C. (1969), "Equivalent axle loads for pavement design", Highway Research Record No. 291, pp. 133-143.

Dormon, G. M. and Metcalf, C. T. (1965), "Design curves for flexible pavements based on layered systems theory", Highway Research Record No. 71, pp. 69-104.

Finn, F. N. (1967), "Factors involved in the Design of asphalt pavement surfaces", NCHRP Report No. 39.

Fox, L. (1948), "Computation of traffic stresses on a simple road structure", Proc. 2nd International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Vol. II, pp. 236-256.

Hagstrom, J., Chambers, R. E. and Tons, E. (1965), "Low modulus pavements on elastic foundations", Highway Research Record No. 71, pp. 172-192.

Haley, J. F. (1963), "Frost considerations in highway pavement design: Eastern United States", Highway Research Record No. 33, pp. 1-15.

Hank, R. J. and Scrivner, F. H. (1948), "Some numerical solutions of stresses in two- and three-layered systems", Proc. HRB, Vol. 128, pp. 457-468.

Helmer, R. A. (1965), "Results of Oklahoma flexible paving research project", Highway Research Record No. 71, pp. 39-68.

Heukelom, W. (1961), "Analysis of dynamic deflections of soils and pavements", Geotechnique, Vol. II, pp. 224-243.

Heukelom, W. and Foster, C. W. (1960), "Dynamic testing of pavements", Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 86, No. SM1, pp. 1-28.

(1962), Proc. St. Louis Conference, HRB Special Report No. 73, Appendix B, p. 409.

Holbrook, L. F. (1969), "Prediction of subjective response to road roughness by use of the rapid travel profilometer", Highway Research Record No. 291, pp. 212-226.

Housel, W. S. (1962), "Cumulative changes in rigid pavements with age and time", HRB Bulletin 328, pp. 1-23.

Huang, Y. H. (1969), "Computation of equivalent single-wheel loads using layered theory", Highway Research Record No. 291, pp. 144-155.

Irick, P. E. (1964), "An introduction to guidelines for satellite studies of pavement performance", NCHRP Report No. 2.

Irick, P. E. and Hudson, R. W. (1964), "Guidelines for satellite studies of pavement performance", NCHRP Report No. 2A.

Jumikis, A. R. (1967), "Amount of soil moisture transferred in a thermo-osmotic process of freezing as a function of porosity of soil", Highway Research Record No. 209, pp. 86-92.

Jones, R. (1958), "In-situ measurement of the dynamic properties of soils by vibration methods", Geotechnique, Vol. 7, No. 1, pp. 1-21.

Kallas, B. F. and Riley, J. C. (1967), "Mechanical properties of asphalt pavement materials", Proc. 2nd International Conference on Structural Design of Asphalt Pavements, University of Michigan, pp. 791-814.

Karrh, J. B. and Stephenson, H. K. (1967), "Application of AASHO Road Test results to Alabama conditions", Alabama Highway Department, HPR Report No. 22.

Kersten, M. S. and Skok, E. L., Jr. (1968), "Application of AASHO Road Test results to design of flexible pavements in Minnesota", Minnesota Department of Highways, Investigation No. 183.

Kondner, R. L. and Krizek, R. J. (1961), "Non-dimensional techniques applied to rigid plate bearing tests on flexible pavements", HRB Bulletin 289, pp. 80-90.

Kondner, R. L. and Krizek, R. J. (1966), "Factors influencing flexible pavement performance", NCHRP Report 22.

Kruse, C. G. and Skok, E. L., Jr. (1968), "Flexible pavement evaluation with the Benkelman Beam", Minnesota Department of Highways, Investigation No. 603.

Langsner, G., Huff, T. S. and Liddle, W. J. (1962), "Use of Road Test findings by AASHO Design Committee", Proc. St. Louis Conference, HRB Special Report No. 73, pp. 399-405.

(1962), "Materials and construction", Report No. 2, HRB Special Report 61B.

McCullough, B. F. and Van Til, C. J. (1968), "Evaluation of AASHO Interim Guides for design of pavement structures", NCHRP Project 1-11, (unpublished report).

McLeod, N. W. (1963), "Some notes on pavement structural design", Highway Research Record No. 13, pp. 66-141.

McLeod, N. W. (1965), "Some notes on pavement structural design - Part 2", Highway Research Record No. 71, pp. 85-104.

McMohon, T. F. and Yoder, E. J. (1960), "Design of a pressure sensitive cell and model studies of pressures on a flexible pavement subgrade", Proc. HRB, Vol. 39, pp. 650-682.

Morgan, J. R. and Holden, J. C. (1967), "Deflection predictions in prototype pavements", Proc. 2nd International Conference on Structural Design of Asphalt Pavements, University of Michigan, pp. 573-591.

Odemark, N. (1949), "Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity, Statens Vaginstitut, Meddelande No. 77.

Painter, L. J. (1962), "Analysis of AASHO Road Test data by the Asphalt Institute", Proc. International Conference on Structural Design of Asphalt Pavements", University of Michigan, pp. 635-648.

Painter, L. J. (1965), "Analysis of AASHO Road Test data by the Asphalt Institute", Highway Research Record No. 71, pp. 15-38.

(1962), "Pavement Research", Report No. 5, HRB Special Report 61E.

Peattie, K. R. and Jones, A. (1962), "Surface deflections of road structures", Proc. Symposium on Road Tests for Pavement Design, Lisbon, Portugal: Laboratorio Nacional de Engenharia Civil, pp. VIII 1-30.

Peutz, M. G. F., Jones, A. and Van Kempen, H. P. M., (1968), "Layered systems under normal surface loads", Highway Research Record No. 228, pp. 34-45.

Phillips, M. B. and Swift, G. (1969), "A comparison of four roughness measuring systems", Highway Research Record No. 291, pp. 227-235.

Prandi, E. (1967), "The Lacroix - LCPC Deflecrograph", Proc. 2nd International Conference on Structural Design of Asphalt Pavements, University of Michigan, pp. 895-904.

Rizenbergs, R. L. (1961), "Analysis of pavement roughness", Report of the Highway Research Board Laboratory, University of Kentucky.

Scrivner, F. H. and Duzan, H. C. (1962), "Application of AASHO Road Test equations to mixed traffic", Proc. St. Louis Conference, HRB Special Report No. 73, pp. 387-389.

Scrivner, F. H. and Hudson, W. R. (1964), "A report on a modification of the AASHO Road Test serviceability index formula", (paper presented at the January 1964 Annual HRB Meeting).

Scrivner, F. H., Swift, G. and Moore, W. M. (1966), "A new research tool for measuring pavement deflections", Highway Research Record No. 124, pp. 1-27.

Scrivner, F. H. and Moore, W. M. (1966), "A tentative flexible pavement design formula and its research background", Texas Transportation Institute, Research Report 32-7.

Scrivner, F. H. and Moore, W. M. (1966), "Evaluation of the stiffness of individual layers in a specially designed pavement facility from surface deflections", Texas Transportation Institute, Research Report 32-8.

Scrivner, F. H. and Moore, W. M. (1968), "Standard measurements for satellite Road Test programs", NCHRP Report 59.

Sebastyan, G. Y. (1960), "The Benkelman Beam deflection as a measure of pavement strength", Symposium on Pavement Design and Evaluation, Proc. 41st Convention CGRA, pp. 58-70.

Seed, H. B., Mitry, F. G., Monismith, C. L. and Chan, C. K. (1967), "Prediction of flexible pavement deflections from laboratory repeated-load tests, NCHRP Report 35.

Shook, J. F. and Fang, H. Y. (1961), "Cooperative materials testing program at the AASHO Road Test, AASHO Road Test Technical Staff Papers, HRB Special Report 66, p. 59.

Sorbe, V. K. (1967), "The repeatability of test results using various California Bearing Ratio procedures and the Resistance R-value", Utah State Highway Department, Research Report No. 500-908.

Sowers, G. F. (1965), "Georgia Satellite flexible pavement evaluation and its application to design", Highway Research Record No. 71, pp. 151-171.

Spangler, E. B. and Kelly, W. J. (1965), "GMR Road Profilometer - a method for measuring road profile", Highway Research Record No. 121, p. 27.

Swift, G. (1966), "Dynaflect - a new highway deflection measuring instrument", Reprint from Proc. 48th Annual Tennessee Highway Conference, University of Tennessee.

Szendrei, M. E. and Freeme, C. R. (1967), "The computation of road deflections under impulse loads from the results of vibration measurements", Proc. 2nd International Conference on Structural Design of Asphalt Pavements", University of Michigan, pp. 89-99.

Tons, E., Chambers, R. E. and Kamin, M. A. (1965), "Layered pavement design method for Massachusetts", Highway Research Record No. 71, pp. 193-218.

(1962), "Traffic and Operations", Report No. 3, HRB Special Report 61C.

Vaswani, N. K. (1967), "AASHO Road Test findings applied to flexible pavements in Virginia", Virginia Research Council, Interim Report No. 1.

Vesic, A. B. (1963), "Discussion", Proc. International Conference on Structural Design of Asphalt Pavements, 1962, University of Michigan, pp. 283-290.

Walker, R. D., Yoder, E. J., Spencer, W. T. and Lowry, R. (1962), "Significance of layer deflection measurements", HRB Bulletin 321, pp. 63-81.

Warren, H. and Eieckmann, W. L. (1963), "Numerical computations of stresses and strains in a multi-layer asphalt pavement system", Chevron Research Company, (unpublished report).

Westergaard, H. M. (1925), "Computation of stresses in concrete roads", Proc. HRB, Vol. 5, Part 1, pp. 90-112.

Wilkins, E. B. (1962), "Pavement evaluation in Canada", Proc. International Conference on Structural Design of Asphalt Pavements, University of Michigan, pp. 274-350.

Wilson, C. C. (1964), "A dynamic tire force measuring system", Joint Highway Research Project Report No. 6, Purdue University.

Yoder, E. H. and Milhous, R. T. (1964), "Comparison of different methods of measuring pavement condition - Interim Report", NCHRP Report 7.

Zube, E. and Forsythe, R. (1966), "Flexible pavement maintenance requirements as determined by deflection measurement", Highway Research Record No. 129, pp. 60-75.

XIV. VITA

George E. Hunter was born February 4, 1941 in Keene, New Hampshire, the first son of George E. and Jane M. Hunter. He attended elementary and high school in Lancaster, New Hampshire, graduating in 1959.

He received a B.S. degree in Chemistry from Bates College in 1963 and a B.S. degree in Civil Engineering from the University of New Hampshire in 1965.

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