Evaluation and Overlay Design: The Shell Method. Proc., 4th International Conference on the Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, 1977, pp. 649-661.
5. A. I. M. Claessen, C. P. Valkering, and R. Ditmarsch. Pavement Evaluation With the Falling Weight Deflectometer. Proc., AAPT, Vol. 45, 1976, pp. 122-157.
6. C. P. Valkering. Pavement Evaluation by Measuring Deflection and Shape of Deflection Bowl. Proc., 3rd International Conference on the Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, Vol. 2, 1972, pp. 353-356.
7. D. L. De Jong, M. G. F. Peutz, and A. R. Korswagen. Computer Program BISAR: Layered Systems Under Normal and Tangential Surface Loads. Koninklijke/Shell-Laboratorium, Amsterdam, External Rept. AMSR.0006.73, 1973.
8. M. G. F. Peutz, H. P. M. Van Kempen, and A. Jones. Layered Systems Under Normal Surface Loads. HRB, Highway Research Record 228, 1968, pp. 34-45.

Publication of this paper sponsored by Committee on Pavement Rehabilitation Design.

Mechanistic Method of Pavement Overlay Design

Harvey J. Treybig, ARE Inc., Austin, Texas

This paper presents a synopsis of a comprehensive procedure for the rehabilitation design of overlays of both flexible and rigid pavements. The procedure includes an evaluation of the existing pavement by using modern nondestructive deflection testing, condition surveys, and materials sampling and testing. The analytical model on which the computer method is based is elastic-layer theory. This model is used in both the pavement-evaluation and the overlay-thickness analyses. This design and evaluation analysis is unique for various categories of pavement condition. The final overlay thicknesses are selected on the basis of fatigue and rutting criteria where applicable. The entire procedure is automated in a series of three computer programs.

This paper describes the use of a universal procedure for the design of pavement overlays. The detailed development of the criteria for the procedure is discussed and documented in several reports (1-4).

The procedure covers flexible overlays of flexible pavements and both flexible and rigid overlays of rigid pavements. It includes both jointed and continuous rigid pavements and both bonded and unbonded overlays. It covers existing pavements that have remaining life, those that are substantially cracked, and those that are so badly deteriorated that they could be broken mechanically into small pieces. The procedure infers that overlay materials and construction specifications will not differ significantly from those currently used in highway construction. However, it does include some nonconventional materials testing methods.

The comprehensive procedure provides for rehabilitation of existing portland cement concrete (PCC) and asphalt concrete (AC) pavements and is divided into three basic steps: (a) evaluation of the existing pavement, (b) determination of the design inputs, and (c) overlay-thickness analysis. The procedure is illustrated in flowchart form in Figure 1. Evaluation of the existing pavement is accomplished by a condition survey and deflection measurements. This information enables the designer to distinguish among different segments of the existing pavement based on their condition. Each segment becomes a design section and is analyzed separately. Thus, the most economical rehabilitation may involve varying the overlay thickness along the roadway according to the existing pavement condition.

The design inputs include both past and future traffic, environmental considerations, and materials testing and analysis. The results of deflection measurements also serve to aid in establishing properties of the subgrade material.

The overlay-thickness analysis is based on the concepts of failure by excessive rutting (flexible pavements) and by excessive fatigue cracking (rigid and flexible pavements). Stresses and strains in the pavement are computed by using linear elastic-layer theory (5). The overlay life is determined by entering these stresses into a fatigue or rutting equation that relates stress or strain magnitude and repetitions to failure. The overlay thickness that satisfies the fatigue and rutting criteria is selected as the design thickness.

The design procedure is automated in the form of three separate computer programs—PLOT2, TVAL2, and POD1. The programs require the designer to make only minor hand computations, and these are only aids in determining computer-program input data.

GENERATION OF DESIGN-PROCEDURE INPUTS

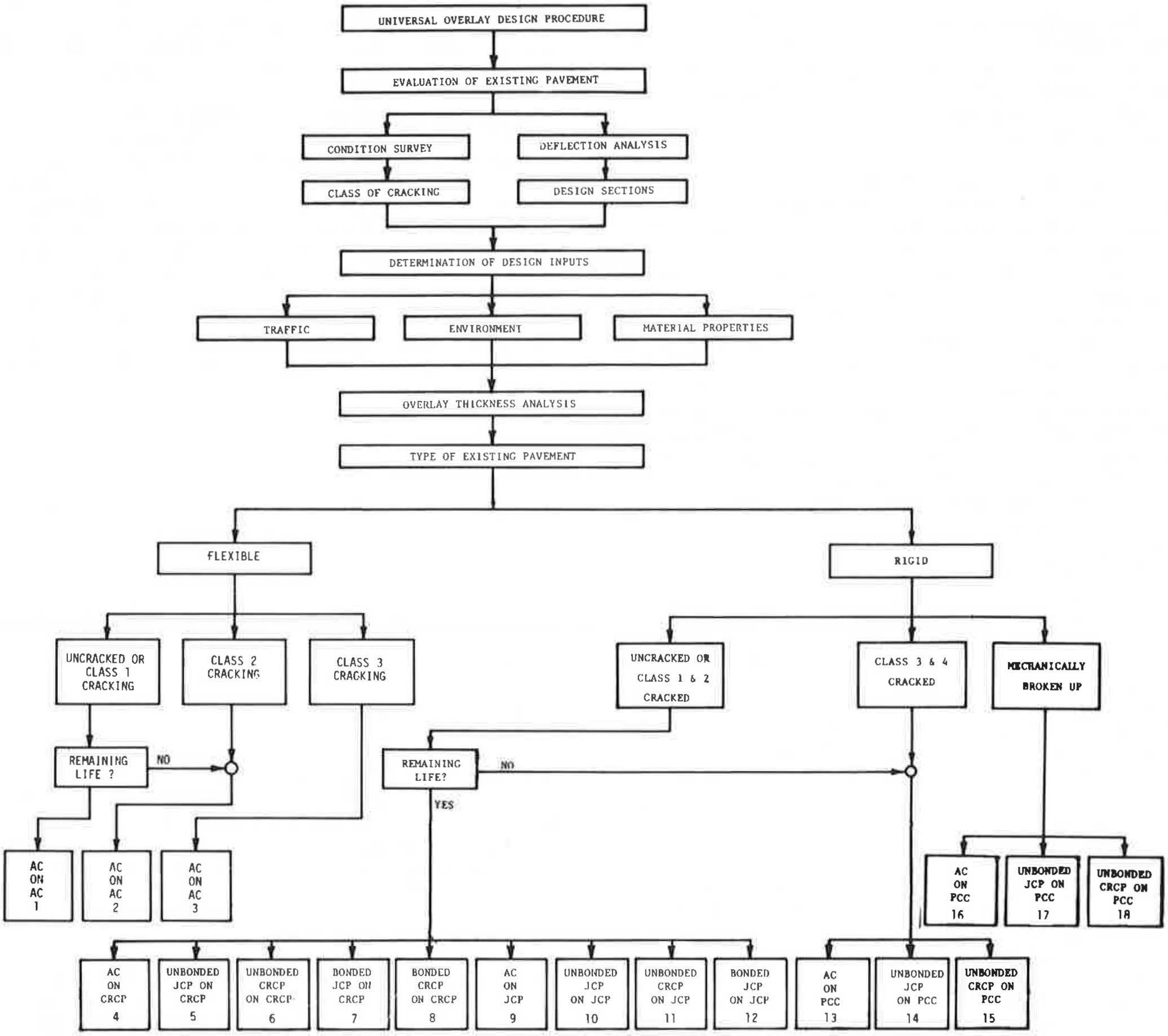
The design procedure requires input from the following three areas: deflection testing, condition surveys, and traffic data.

Deflection Testing

Deflection testing is used to measure the response of the in-service pavement to load. From this behavior pattern, areas that have equal or similar performance and materials properties can be determined.

1. Type of equipment: Any type of deflection-measuring equipment (such as the Dynaflect or the road rater) that gives satisfactory deflection results can be used (6). This type of equipment lends itself to rapid testing, thus making it economically possible to investigate the pavement structure thoroughly. Deflections measured with a Benkleman beam and an 80-kN (18 000-lbf) single-axle load can also be used.

Figure 1. Flowchart of pavement overlay design procedure.



2. Recommended testing conditions: The design procedure is based on measurements that represent the time of year when the deflection values are maximum. It is recommended that the user measure deflections during this time of year. If measurements are made during other seasons, they must be corrected to relate to the worst condition.

3. Sampling frequency and procedure: The recommended testing procedure includes determining at least one deflection profile along the outer wheel path of the existing roadway. The spacing between the measurements should be a maximum of 30.5 m (100 ft). For undivided roadways, it is desirable to obtain two deflection profiles, one in each outside wheel path. The measurements for each profile should be spaced 30.5 m apart, but those for the two profiles should be staggered to provide profile data that has 15.2-m (50-ft) spacings. For divided highways, deflection profiles should be obtained in the outside lanes of both roadways on a staggered basis.

For undivided highways, the two deflection profiles should be combined into one that represents the entire width of roadway. However, for divided highways, the profiles for the pavements on either side of the median should be considered separately. Two profiles will give adequate coverage of most highways. The measurements, however, should be made at locations between cracks or joints in a good portion of the pavement and at regular intervals and so documented. A suggested guideline for spacings for deflection tests is given below (1 m = 3.3 ft).

Type of Location	Spacing (m)
Rolling terrain	30.5
Numerous cut-to-fill transitions	30.5
Level with uniform grading	76.2

In addition to the measurements for the determination of a deflection profile, it is also necessary to make measurements at the corners of a jointed concrete pavement (JCP). These data are used in determining the degree of load transfer. Corner measurements should be kept separate and not included in the deflection profile, but should be made at the same time as the interior measurements.

Condition Surveys

Condition-survey information should be obtained that includes such items as an accurate inventory of the different types and amounts of cracking, rutting, spalling, joint condition, faulting, pumping, and blowups and some inventory of roughness. [Condition-survey techniques are described elsewhere (7).]

1. Cracking in rigid pavements: Cracking is defined and recorded according to the American Association of State Highway Officials (AASHO) definitions, i.e., class 1, class 2, class 3, and class 4 (8).

Class 1 includes fine cracks that are not visible under dry surface conditions by a person who has good vision and is standing at a distance of 4.6 m (15 ft). Class 2 cracks are those that can be seen at a distance of 4.6 m but exhibit only minor spalling such that the opening at the surface is less than 6.4 mm (0.25 in). A Class 3 crack is defined as a crack opened or spalled at the surface to a width of 6.4 mm or more over a distance equal to at least one-half the crack length, except that any portion of the crack opened less than 6.4 mm at the surface for a distance of 0.9 m (3 ft) or more is classified separately. A class 4 crack is defined as any crack that has been sealed.

2. Cracking in flexible pavements: As for rigid pavements, cracking is defined and recorded according to the AASHO definitions. Class 2 cracking (commonly referred to as alligator cracking) is defined as that which has progressed to the stage where the cracks have connected together to form a grid-type pattern. Class 3 cracking is the progression from class 2 in which the class 2 cracks spall more severely at the edges and lose integrity between blocks and the segments of pavement surface loosen and move or rock under traffic.

The condition surveys provide important data for explaining variations in the deflection profiles and also differences in materials properties determined in laboratory investigations. A comparison of the deflection profile and the observed distress should be considered in formulating the materials sampling plan. Furthermore, the type of cracking observed on the existing surface becomes a decision criterion relative to the method of characterization of the existing pavement and the kind of analysis to be performed.

3. Rutting: The rutting measurements in wheel paths on existing AC surfaces are included in the condition survey to give (a) insight into the selection of an allowable rut depth and (b) an estimation of the leveling up that will be required on the existing surface before it is overlaid. It is recommended that the rut depth be measured every 152 m (500 ft) in both wheel paths and that the averages for the two wheel paths be determined for the same pavement lengths as the design sections established from the deflection profiles as described below. These measurements can be made by simple mechanical devices similar to those used at the AASHO Road Test. An alternative method is to lay a stringline or other long straightedge across the wheel path and measure the rut depth with a scale.

4. Environmental data: If the existing pavement is AC, it is necessary to obtain temperature information. The number of days per year that the average daily temperature exceeds 18°C (64°F) must be determined for use in the rutting analysis. These data can usually be obtained from past weather records.

Traffic Information

The traffic information required for the design procedure is described in terms of the number of 80-kN equivalent single-axle loads (ESALs) determined in accordance with the Interim Guide for the Design of Pavement Structures (9). The number of load applications already experienced on the existing surface must be estimated. The number of load applications must also be projected for the anticipated life of the overlay.

If the traffic projection represents the total of all lanes for both directions of travel, the traffic must be distributed by direction and lane for design purposes. Directional distribution is normally made by assigning 50 percent to each direction unless special conditions warrant some other distribution. In regard to lane distribution, the outside lane is generally the controlling lane. If an agency has available lane-distribution factors for facilities that have two or more lanes in each direction, these should be used. If not, the guideline below can be used; if there is doubt as to which factor to apply, it is suggested that the more conservative range be used.

Number of Lanes in One Direction	Lane-Distribution Factor
2	1.0
3	0.8-1.0
More than 3	0.4-0.6

SELECTION OF DESIGN SECTIONS

By using the nondestructive deflection test data, a highway can be divided into different design sections, i.e., areas where the pavement responds differently to load.

Deflection Profiles

The deflection data obtained in the site investigations, excluding joint deflections, are plotted in the form of profiles throughout the length of the roadway as shown in Figure 2. Profiles from separate lanes should be combined according to location or station number. These plots can be made manually or by using the computer program PLOT2.

Preliminary Design Sections

The deflection profiles are divided into areas that have similar deflections. Information from the condition survey can be used as an additional guideline for dividing the profile into sections. These sections should also be compared with cracking surveys to show whether there are differences in deflection and performance of the pavement. Areas that have significantly different cross sections should be assigned different sections of deflection profile.

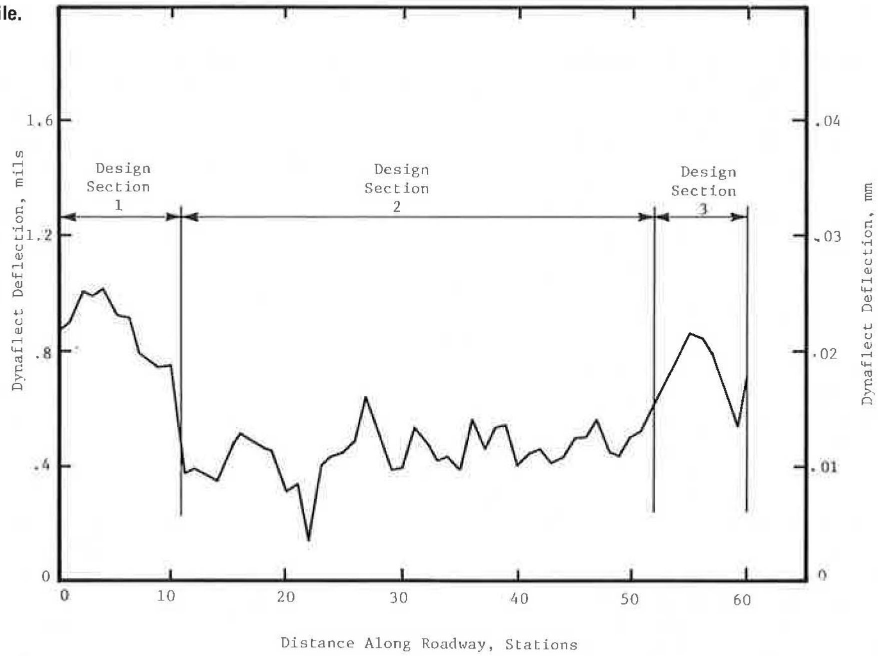
Statistical Hypothesis Testing

Adjacent design sections that have the same cross section should be tested to determine whether they are significantly different or whether they are from the same population of data. This can be done by using a standard statistical method for testing the significance of the difference between two samples, such as the hypothesis tests for equal means (10).

The designer selects the significance level at which the deflection differences are to be tested; a level of 5 percent is recommended for general use. The statistical test can be made either by hand or by use of the computer program TVAL2 (7).

If two adjacent sections are not significantly different, they should be combined into one and that one tested against the next adjacent section. This procedure establishes the design sections, each of which becomes

Figure 2. Sample deflection profile.



a separate design problem.

Determination of Design Deflection

The standard deviations of the deflections are an indication of the variations that exist within the design sections. The design deflection for any given roadway section is a function of the mean deflection, the variation, and the confidence level selected for design:

$$W_\alpha = \bar{w} + zS_{dw} \quad (1)$$

where

W_α = design deflection based on Dynaflect or Benkleman beam measurements (in),
$\bar{W}$ = mean deflection (in),
z = distance from mean to selected significance level on a normal distribution curve, and
S_{dw} = standard deviation of mean deflection (in).

(The z-values for use with Equation 1 have been determined for U.S. customary units only.)

The z-values corresponding to various design confidence or reliability levels are given below.

Confidence Level	z-Value
50	0
75	0.674
90	1.282
95	1.645
97.5	1.960
99	2.330

MATERIALS SAMPLING AND TESTING

Sampling Plan

Normally, the design sections should be established before sampling is planned. It is recommended that at least one boring be made in each design section and, for extremely long sections, more than one boring may be desirable.

The borings should include cores of any paving layers that are intact, such as (a) existing asphalt or concrete, (b) cement-stabilized materials, (c) asphalt-stabilized materials, or (d) other chemically treated materials. Any granular or gravel layers should be sampled by collection of augered materials from the drill hole. Unbound materials should be sampled in sufficient quantity for remolding of specimens; this requires the in-place moisture content and the density, which are easily obtained if nuclear equipment is available. For materials where it is possible to push tubes, undisturbed samples should be obtained. The drill hole should be carefully logged so as to accurately document the layer thick nesses in the existing pavement structure. Normally a total depth of 1.5-2.1 m (5-7 ft) is sufficient for pavement borings.

Asphalt Concrete and Portland Cement Concrete Testing

The materials properties required for the AC are its Poisson's ratio and modulus of elasticity; those for the PCC are its Poisson's ratio, modulus of elasticity, and flexural strength.

1. Modulus of elasticity: The dynamic modulus of elasticity of the AC material should be determined. Currently, there is no American Society for Testing and Materials standard for this test, but there are established procedures. The designer should determine the modulus over a range of temperatures and then use the modulus based on his or her selected temperature(s). A temperature of 21°C (70°F) is suggested for design. Recommended procedures are given elsewhere (7). The modulus of elasticity for PCC can be determined according to ASTM C469, and the flexural strength can be determined according to ASTM C78.

2. Poisson's ratio: Normally, tests are not performed for Poisson's ratio because it does not vary significantly. It is recommended that a value of 0.3 be used for AC and of 0.15 for PCC in the design analyses. The overlay-design computer program has default values of 0.3 and 0.15 built in for the Poisson's ratios of asphalt and concrete, respectively.

Base-Material Testing

The moduli of elasticity of all base and subbase materials must be determined. Poisson's ratio tests are not necessary. Default values in the computer program are 0.20 for stabilized bases and 0.40 for granular bases.

1. Unbound materials: Normally, base and subbase materials will be disturbed samples and thus require recompaction. The in-place density and moisture content should be determined if possible and the materials remolded at these values; otherwise, samples should be recompacted at the optimum moisture content and not less than 95 percent of the density corresponding to that moisture content as used for construction control. Base and subbase materials should be tested at confining pressures equal to the overburden pressure unless that is less than 6.9 kPa (1 lbf/in^2), when the tests should be unconfined. The tests should be performed at a deviator stress of 138 kPa (20 lbf/in^2) if the total concrete thickness is 15 cm (6 in) or less or 69 kPa (10 lbf/in^2) if it is greater than 15 cm (7).
2. Subgrade materials testing: Disturbed subgrade samples should be treated similar to base materials. Undisturbed subgrade samples should be tested at confining pressures equal to the overburden and over a range of repeated deviator stresses [e.g., 13.8-82.7 kPa (2-12 lbf/in^2)]. The laboratory tests should be performed at a minimum of four levels of deviator stress; 13.8, 34.4, 55.2, and 82.7 (2, 5, 8, and 12 lbf/in^2) are recommended. A default value of 0.45 is used for Poisson's ratio of the subgrade.

DESIGNATION OF OVERLAY DESIGN CATEGORY

Existing Pavement Classification

The use of the design procedure requires that each design section of the existing pavement be classified into one of the following categories:

1. Remaining-life PCC—a PCC pavement that is uncracked or has class 1 or 2 cracking as defined in the AASHO guide,
2. Cracked PCC—a PCC pavement that has class 3 or 4 cracking as defined in the AASHO guide (the program can change a design section originally in category 1 to this category if the calculated remaining life of the existing pavement is less than a preestablished minimum),
3. Mechanically broken PCC—a PCC pavement in such poor condition that the designer feels it should be broken up to serve as a base material before overlay (repair or removal and replacement of the damaged portions may instead be used to upgrade the section to category 2),
4. Remaining-life AC—an AC pavement that is uncracked or shows less than 5 percent class 2 cracking,
5. Mildly cracked AC—an AC pavement that has more than 5 percent class 2 cracking but less than 5 percent class 3 cracking [if the cracked areas are removed and replaced to meet the conditions specified for category 4, then the analysis for category 4 (remaining life) can be used], and
6. Severely cracked AC—an AC pavement that shows more than 5 percent class 3 cracking (pavements in this category can be upgraded to category 5 or category 4 by appropriate repair or removal and replacement of the damaged portions).

Types of Overlay Analysis

The category assigned to the existing pavement and the types of materials for the existing pavement and the overlay, all of which are required design inputs, determine the type of overlay analysis. In addition, for pavement sections designated as remaining-life pavements, the number of 80-kN ESALs to date affects the internal section of the analysis in the calculation of the fraction of remaining life. If this fraction is less than a preassigned minimum, the section is no longer considered to be a remaining-life case.

A total of 18 overlay analysis types are considered: 9 for PCC remaining-life pavements, 3 for PCC that has class 3 or 4 cracking, 3 for PCC that will be mechanically broken up, 1 for AC remaining-life pavements, 1 for mildly cracked AC, and 1 for severely cracked AC.

If the existing pavement is a remaining-life CRCP, AC, bonded or unbonded jointed concrete pavement (JCP), and bonded or unbonded CRCP are acceptable overlays. If the existing pavement is a remaining-life JCP, AC, bonded or unbonded JCP, and unbonded CRCP are acceptable overlays. If the existing pavement has class 3 or 4 cracking or will be mechanically broken up, AC, unbonded JCP, and unbonded CRCP are acceptable overlays, but bonded JCP and bonded CRCP are not. Only AC overlays are permitted on AC existing pavements. Rigid overlays over existing flexible pavements must be treated as new pavement designs, not as overlays.

USE OF OVERLAY-DESIGN COMPUTER PROGRAM POD1

The program POD1, described in detail elsewhere (7), is used to determine the overlay thickness needed to satisfy the design criteria. For PCC existing pavements, only a fatigue-cracking criterion is used; for AC existing pavements, both fatigue and rutting criteria are used, and the larger of the thicknesses required by the two criteria is used in the final design.

Outline of Program Operation

POD1 performs the following operations:

1. It determines the subgrade modulus under the design load from the design deflection, the measured characteristics of the subgrade soil, and the characteristics of the deflection and design loads.
2. It computes the fraction of remaining life in the existing pavement from stresses in the pavement before overlay, when appropriate.
3. It calculates the stress (strain for AC pavements) in the pavement system for the design load (an 80-kN ESAL) for overlay thicknesses of 7.6-30.5 cm (3-12 in).
4. It determines the fatigue life from the stress or strain for each overlay thickness and the rutting life (life to specified rut depth) for AC pavements in categories 5 and 6 (the rutting model is not applicable to category 4).
5. It plots lifetimes against overlay thicknesses and interpolates for thicknesses corresponding to the design-lifetimes input.

Summary of Input Information

The information needed to determine input values for POD1 is summarized below:

1. The design deflection as determined by using PLOT2, TVAL2, and Equation 1 for the design deflection;
2. The load magnitude, tire pressure, and wheel

configuration of the deflection-measuring device;

3. The condition of the existing pavement surface, i.e., whether or not it is cracked, the type of cracking if present, and whether it will be mechanically broken before overlay;

4. If the existing pavement is JCP, the ratio of the corner deflection to the interior deflection;

5. The presence or absence of voids beneath the existing pavement;

6. The number of 80-kN ESALs the pavement has experienced to date and the number that it is being designed to accept before failure;

7. If the existing pavement is AC, the allowable rut depth before rutting failure is assumed and the number of days per year that have a mean temperature greater than 17° C;

8. The material type, thickness, Poisson's ratio, and modulus for each layer in the existing system;

9. For the subgrade material, the laboratory-determined deviator stresses and corresponding modulus values;

10. If the existing pavement is PCC, the flexural strength;

11. The type of overlay and its modulus, Poisson's ratio, and flexural strength; and

12. The type of bond breaker, if used, and its thickness, modulus, and Poisson's ratio.

The program contains default values for the Poisson's ratio values based on material types and for bond breaker thickness and modulus. If the condition survey has shown the existing pavement to be a class 3 or 4 cracked PCC or one that will be mechanically broken up or a class 2 or 3 cracked AC, the modulus value that is input for the surface layer will automatically be defaulted to a predetermined value.

Program POD1 has been written so that the required data can be input in a simple, yet logical, manner. Problems that deal with nearly similar situations can be stacked by, for each problem, inputting only the directives (data input cards) that contain the item that is changed from the first problem. For any one problem, the directives can appear in any order except that a PROBLEM directive must begin the data for every problem and an END directive must follow the data for the last problem.

Program Execution Information

POD1 requires approximately 50 000 octal (about 21 000 decimal) words of memory on a CDC CYBER 74 or CDC 6600 computer and uses 8-10 s of central processing unit time for a complete problem for a rigid pavement. Flexible pavement problems may take somewhat longer, especially if rutting computations are involved. If the subgrade modulus for the first problem of several stacked together is applicable for the remaining problems, those remaining will execute in approximately 4 s each.

No peripheral equipment is required except a card reader and a line printer. If the program is on a permanent file, it can be executed from a remote terminal; the output is relatively compact and can be printed easily.

ACKNOWLEDGMENT

This paper is a synthesis of the results of extensive research on pavement rehabilitation design. The research was originally sponsored by the Office of Research and Development, Federal Highway Administration, under a federally coordinated program project. The contract manager was Richard A. McComb. The work was accomplished by a staff of key persons including Phil Smith, B. F. McCullough, Harold Von Quintus, Frank Carmichael, Peter Jordahl, and Jack O'Quin.

REFERENCES

1. Austin Research Engineers, Inc. Asphalt Concrete Overlays of Flexible Pavements: Volume 1—Development of New Design Criteria. Federal Highway Administration, Rept. FHWA-RD-75-75, June 1975. NTIS: PB 263 432/7SL.
2. H. J. Treybig, B. F. McCullough, R. P. Smith, and H. Von Quintus; Austin Research Engineers, Inc. Overlay Design and Reflection Cracking Analysis for Rigid Pavements: Volume 1—Development of New Design Criteria. Federal Highway Administration, Rept. FHWA-RD-77-66, Aug. 1977.
3. Austin Research Engineers, Inc. Asphalt Concrete Overlays of Flexible Pavements: Volume 2—Design Procedures. Federal Highway Administration, Rept. FHWA-RD-75-76, June 1975. NTIS: PB 263 433/5SL.
4. H. J. Treybig, B. F. McCullough, R. P. Smith, and H. Von Quintus; Austin Research Engineers, Inc. Overlay Design and Reflection Cracking Analysis for Rigid Pavements: Volume 2—Design Procedures. Federal Highway Administration, Rept. FHWA-RD-77-67, Aug. 1977.
5. H. Warren and W. S. Eieckman. Numerical Computation of Stresses and Strains in a Multiple-Layered Asphalt Pavement System. California Research Corporation, Richmond, Sept. 1963.
6. F. H. Scrivner and W. M. Moore. An Electro-Mechanical System for Measuring the Dynamic Deflection of a Road Surface Caused by an Oscillating Load. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 32-4, 1964.
7. H. J. Treybig, B. F. McCullough, P. R. Jordahl, R. P. Smith, and H. Von Quintus. Flexible and Rigid Pavement Overlay Design Procedure. Federal Highway Administration, Rept. FHWA-RD-77-133, Oct. 1977
8. The AASHO Road Test: Report 5—Pavement Research. HRB, Special Rept. 61E, 1962.
9. Interim Guide for Design of Pavement Structures. AASHO, 1972.
10. H. L. Alder and E. B. Roessler. Introduction to Probability and Statistics. W. H. Freeman and Company, San Francisco, 3rd Ed., 1965.

Publication of this paper sponsored by Committee on Pavement Rehabilitation Design.