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USE OF DEFLECTION BASIN CHARACTERISTICS FOR FLEXIBLE PAVEMENT ANALYSIS AND OVERLAY DESIGN

MICHIGAN
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TESTING AND RESEARCH DIVISION
RESEARCH LABORATORY SECTION

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USE OF DEFLECTION BASIN CHARACTERISTICS FOR FLEXIBLE PAVEMENT ANALYSIS AND OVERLAY DESIGN

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Introduction

For several years Benkelman beam measurements have been used by the Laboratory to evaluate the structural capacity of flexible pavements (1, 2). Because of their value and our planned continued use of these techniques, it was thought desirable to provide a description of the procedures and their applications to certain research projects as a reference for future studies in similar areas of research.

Although there are several recently developed procedures for the analysis of flexible pavements based on deflection measurements, all involve a similar three-step procedure. First, the deflection measurements are made at selected test sites on the road, using loads of known magnitude, duration, and area of loading. Next, the measured deflections, which are a function of the loading and of the stiffness parameters of the total pavement system, are used to compute the structural parameters for the pavement system.

Estimated layer properties are then used to compute theoretical deflection values which should match the measured pavement deflections. Values for the layer properties can be adjusted and deflections recomputed until a satisfactory matching with measured deflections is obtained. In this process, the material properties of the granular layers and the subgrade are estimated from the measured response of the structure, in this case, the measured deflections of the pavement. Bituminous layers, easily sampled by coring and readily tested in the laboratory, provide measured values in this procedure which enhance the reliability of estimates made for the granular and subgrade layer properties. The granular and subgrade layers are difficult and time consuming to sample and adequate laboratory test procedures are the subject of current research. This procedure obviates the need for laboratory tests on the granular and subgrade layers. Finally, the pavement parameters are used, in appropriate layer analysis models, to compute strain levels generated at critical points in the system. Pavement life, in terms of a reference axle load, is then estimated from the strain levels using criteria developed through extensive laboratory and test road performance evaluations.

For each of these three steps there are several procedures that have been used by various agencies (3). Deflection measurement systems range from the relatively simple Benkelman beam and load truck combination, to the "Thumper," a sophisticated system developed for the Federal Highway Administration which utilizes an electrohydraulic servo-controlled loading system with several LVDT displacement transducers mounted on a reference beam. The entire mechanism is contained in an air-conditioned motor home and operated entirely from the driver's seat. Other load-deflection devices include the Dynaflect, Roadrater, and the Falling Weight Deflectometer, all of which are highly mechanized, self-contained units for rapidly loading the pavement and recording resulting deflections. Deflection values used in pavement analyses range from the maximum deflection, as measured directly under the wheel load, to more complex schemes using the shape and magnitude of the deflection basin within several feet of the load.

Estimation of the stiffness moduli of the pavement layers can also be made using the deflection data in several different ways. In addition to using only the maximum deflection (the term deflection is used by many agencies to mean the maximum deflection), other analysis schemes use the radius of curvature of the deflected surface (4, 5), the area under the deflection curve (3, 6), and the ratios of deflections at different points on the deflection basin curve (7). Laboratory tests are sometimes used to supplement the information obtained from field deflection measurements; the difficulty, however, in obtaining samples and in duplicating field conditions for granular layers in the laboratory makes the results highly questionable. Asphalt-bound surface and base layers, on the other hand, can be readily cored and tested for stiffness and Poisson's ratio in the laboratory.

Both analysis and design techniques are similar for all methods of flexible pavement evaluation. A computer program is used to calculate strain levels at critical points in the pavement layers from which pavement life, in terms of standard 18-kip equivalent axle loads, is estimated using fatigue and rutting failure models which have been developed either by test road studies or laboratory testing programs. Several investigators have developed graphic solutions which directly relate deflection measurements to strain values (4, 8). These solutions are the result of computer analyses performed for ranges of typical layer thicknesses and moduli values.

Methods for analyzing and interpreting the deflection basin data used in this report are based largely on concepts developed by S. S. Kuo during research work conducted prior to his leaving the Research Laboratory.

Method for Flexible Pavement Analysis

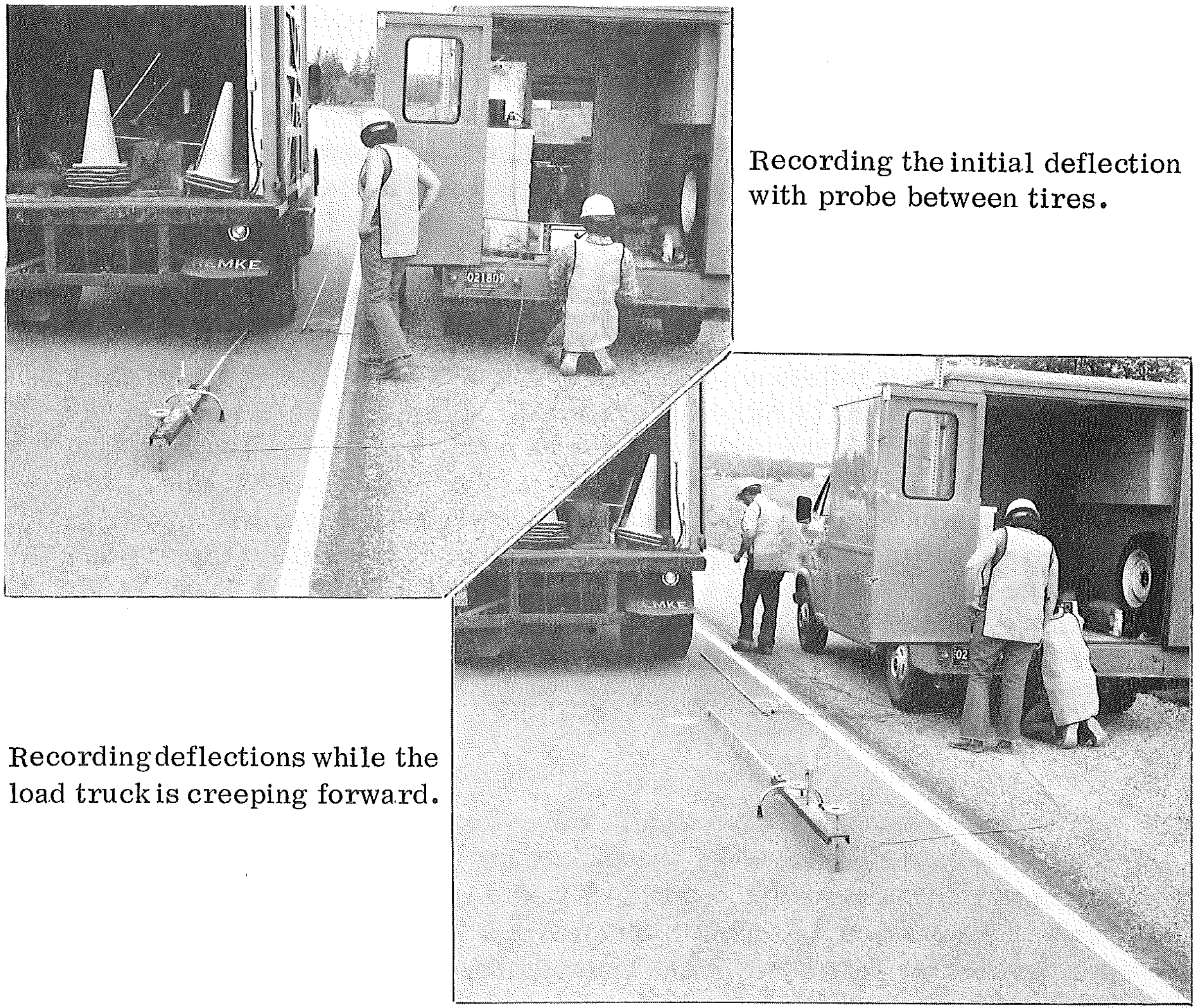
The method described here involves the three basic steps previously discussed: 1) deflection measurements, including material sampling and layer thickness measurements; 2) determination of pavement layer parameters using deflection measurements together with laboratory test data for the bituminous paving materials; and, 3) analysis of the existing pavement and/or the design of paving layers to be added, using established models which relate pavement strains with expected life.

Factors that influence the results of the method include pavement temperature and loading duration. Bituminous mixtures are viscoelastic; their stiffness, or resistance to deformation under a given load, depends on both temperature and the length of time the load is applied. Therefore, both vehicle speeds and pavement temperatures must be accounted for during deflection testing and throughout pavement life. Laboratory test results for bituminous mixtures are affected by rate of loading and loading time duration, and sample temperature, and these factors must be reconciled with field conditions during deflection testing. Means of accounting for the effects of these factors are included in the procedure described in the following basic steps.

Seasonal variations can significantly affect results. Deflection tests should not be performed when soil and granular materials are frozen as an extremely unrealistic high degree of stiffness would be indicated for the road. Spring or early summer are generally considered the most appropriate times for deflection measurements since the granular and soil layers are high in moisture content; the indicated roadway stiffness would be less than during the drier late summer period and would provide realistic but somewhat conservative values for design purposes.

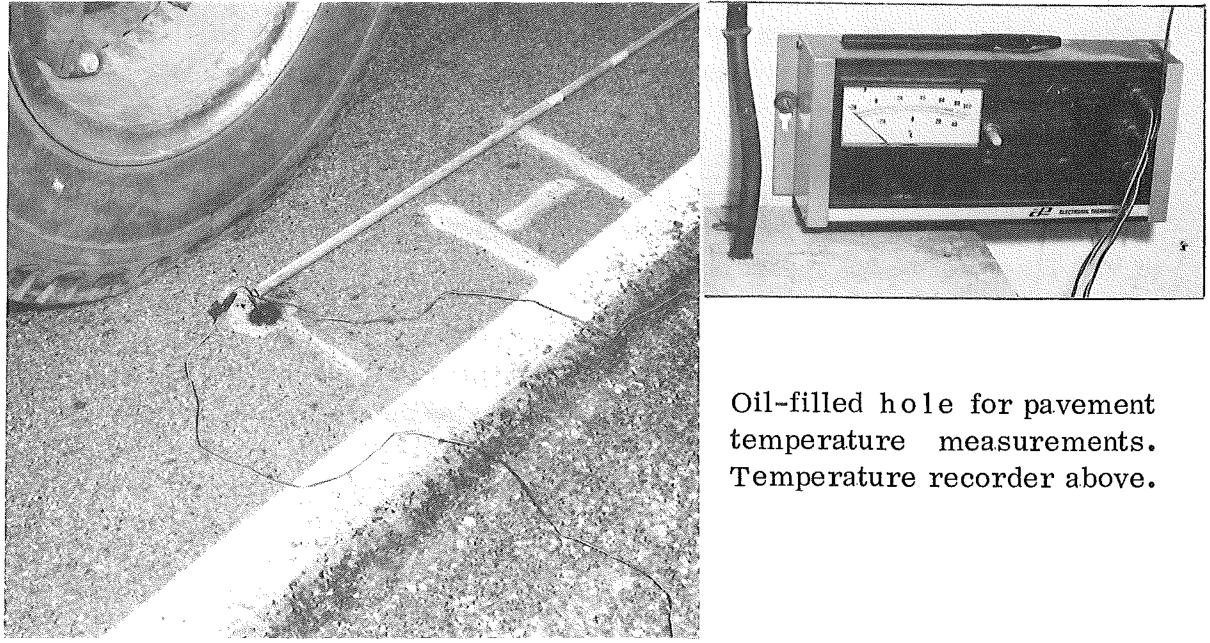
Step 1. Field Deflection Measurements – Benkelman beams are used to measure deflection under an 18-kip single axle load. Core sampling of the pavement and measurement of layer thicknesses are done in conjunction with these deflection measurements.

A 9,000-lb dual wheel load is placed over the location to be tested. The pointer of the Benkelman beam is placed between the dual wheels slightly ahead of the center of the axle. The beam and recording equipment are then calibrated and the pavement marked in 1-ft intervals. The load truck is driven slowly forward and the rebound deflection continuously recorded. Details of the procedure are given in Appendix A. Figure 1 shows the equipment and operations involved in the deflection test.



Recording the initial deflection with probe between tires.

Recording deflections while the load truck is creeping forward.



Oil-filled hole for pavement temperature measurements. Temperature recorder above.

Figure 1. Measuring deflections of a flexible pavement using the Benkelman beam.

Step 2. Estimating Layer Stiffness Values — Estimation of the stiffness of each of the pavement layers is a process that involves the matching of computed deflections with deflections measured with the Benkelman beam. Trial modulus values for each layer are used in the CHEV 5L computer program (9, 10) and deflections are computed for comparison with Benkelman beam deflections. CHEV 5L enables designers to calculate stresses, strains, and displacements at any position in a multilayer system, with an arbitrary number of layers subjected to a single normal load. In the case of dual tire loadings, CHEV 5L is run for each point load and the effects of the adjacent tire load accounted for by the principle of superposition. The input parameters for the CHEV 5L program are traffic loading, tire pressure, number and thickness of layers in the flexible pavement cross-section, the resilient modulus E, and Poisson's ratio, μ, of each component layer. The determination of values to assume for the resilient modulus of each layer was a major portion of this study. Modulus values are adjusted until satisfactory agreement between field and computed deflections is achieved, thus assuring that reasonably correct values are being used in the pavement life analysis estimate.

Bituminous surface courses and black base materials are tested in the laboratory for stiffness moduli using the core samples obtained from Step 1. For the design of new construction or for a proposed overlay, the modulus of the proposed mix can be estimated from the asphalt cement properties (penetration and viscosity) and mix design proportions of aggregate and asphalt in accordance with the procedure in Appendix B.

For the granular base and subbase layers, modulus values can be calculated from stress-dependent relationships that were developed by the U. S. Waterways Experiment Station (11). This method was developed in accordance with the concept that the modulus value of unbound granular materials is stress-dependent and that, since induced stresses decrease with depth, modulus values also decrease with depth. This implies that the modulus of the granular material in each layer is a function of the layer thickness and of the modulus of the underlying layer. Therefore, the modulus of the subbase layer directly over the subgrade is a function of the subgrade modulus and the modulus of the base layer is a function of subbase modulus.

The relationships are expressed mathematically as:

$$E_n = E_{n+1} (1 + 10.52 \log t - 2.10 \log E_{n+1} \log t) \qquad (1)$$

where the base course is layer n. For subbase materials

$$E_n = E_{n+1} (1 + 7.18 \log t - 1.56 \log E_{n+1} \log t) \qquad (2)$$

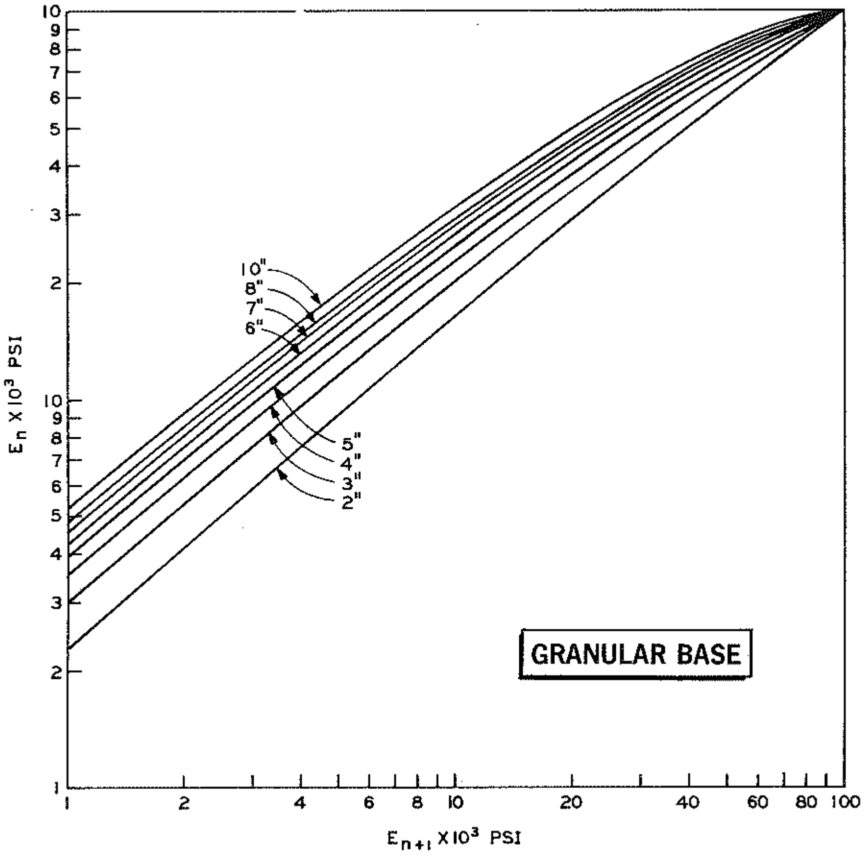


Figure 2. Relationship between modulus of layer n and modulus of layer n+1 for various thicknesses of unbound base course.

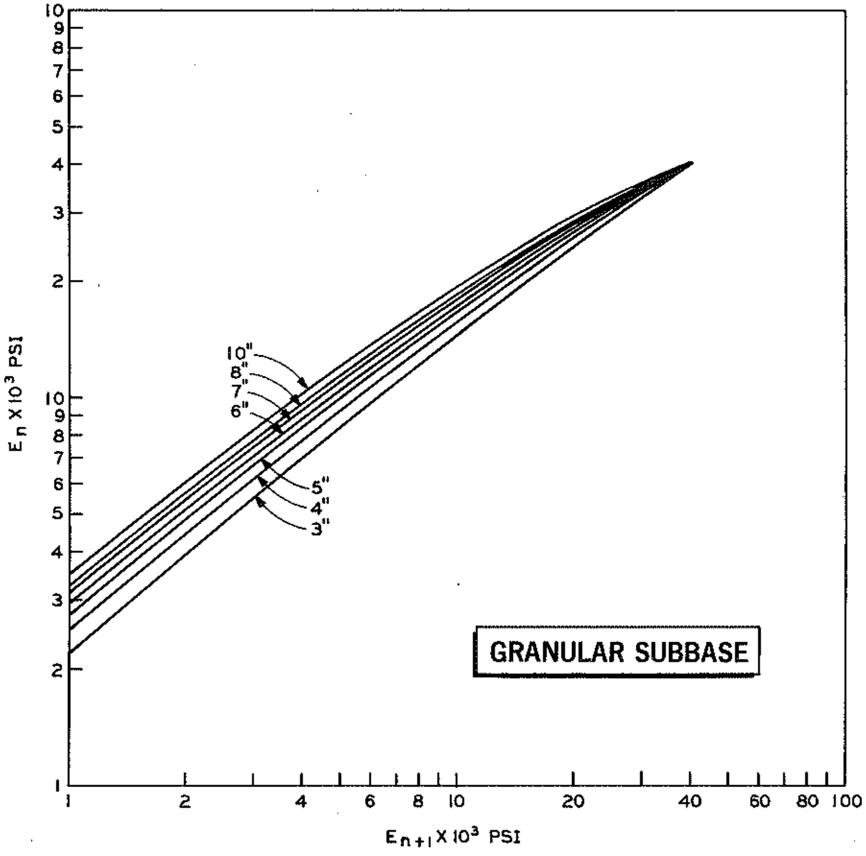


Figure 3. Relationship between modulus of layer n and modulus of layer n+1 for various thicknesses of unbound subbase course.

where the subbase course is layer n. For each equation, E_{n+1} is the modulus value of the lower layer n+1, in psi; t is the thickness of the overlying layer n, in inches; and E_n is the modulus value of layer n, in psi.

For thick granular base and subbase layers, each layer should be divided into sublayers, 6 to 8 in. thick, and the modulus of each sublayer assumed to be a function of its thickness and the modulus of the sublayer below it.

Equations (1) and (2), plotted in Figures 2 and 3, show the relationship of modulus and depth for 2 to 10 in. of unbound base and 3 to 10 in. of unbound subbase. It should be mentioned that the relationships given by Eqs. (1) and (2) do not always yield computed deflection basins which match the actual basin measured on the road. Equations (1) and (2) can be used to match maximum deflections only, and will generally give valid but conservative design results. The example problem presented at the end of this report will show an alternate method of estimating the modulus of the granular layers and will also compare results with those obtained using Eqs. (1) and (2).

The shape of the deflection basin can be described by its maximum deflection and by its spreadability, S, defined as follows (1):

$$S = \frac{d_0 + d_1 + d_2 + d_3 + d_4}{5d_0} \times 100 \qquad (3)$$

where $d_0 + d_1 + . . . d_4$ are the maximum deflection and deflection at 1, 2, 3, and 4 ft from the load. Spreadability, S, and maximum deflection, d_0, can be related theoretically to subgrade modulus and asphalt surface modulus as shown in Figure 4. If surface modulus, E_1, is known then a similar chart can be prepared to estimate the modulus of granular layers such as shown in Figure 5.

Using the layer thicknesses measured in the field (or from plan cross-sections) various combinations of surface modulus (or granular layer modulus), and subgrade modulus can be used in the CHEV 5L program to compute spreadability-deflection coordinates for constructing the Spreadability-Maximum Deflection chart applicable to the pavement being analyzed. The stress-dependent relationships are used for each subgrade modulus to compute base and subbase moduli.

Finally, the spreadability and maximum deflection values obtained from the Benkelman beam measurements are entered on the Spreadability-Maximum Deflection chart, point X in Figure 4, to estimate the E_1 and E_4 values.

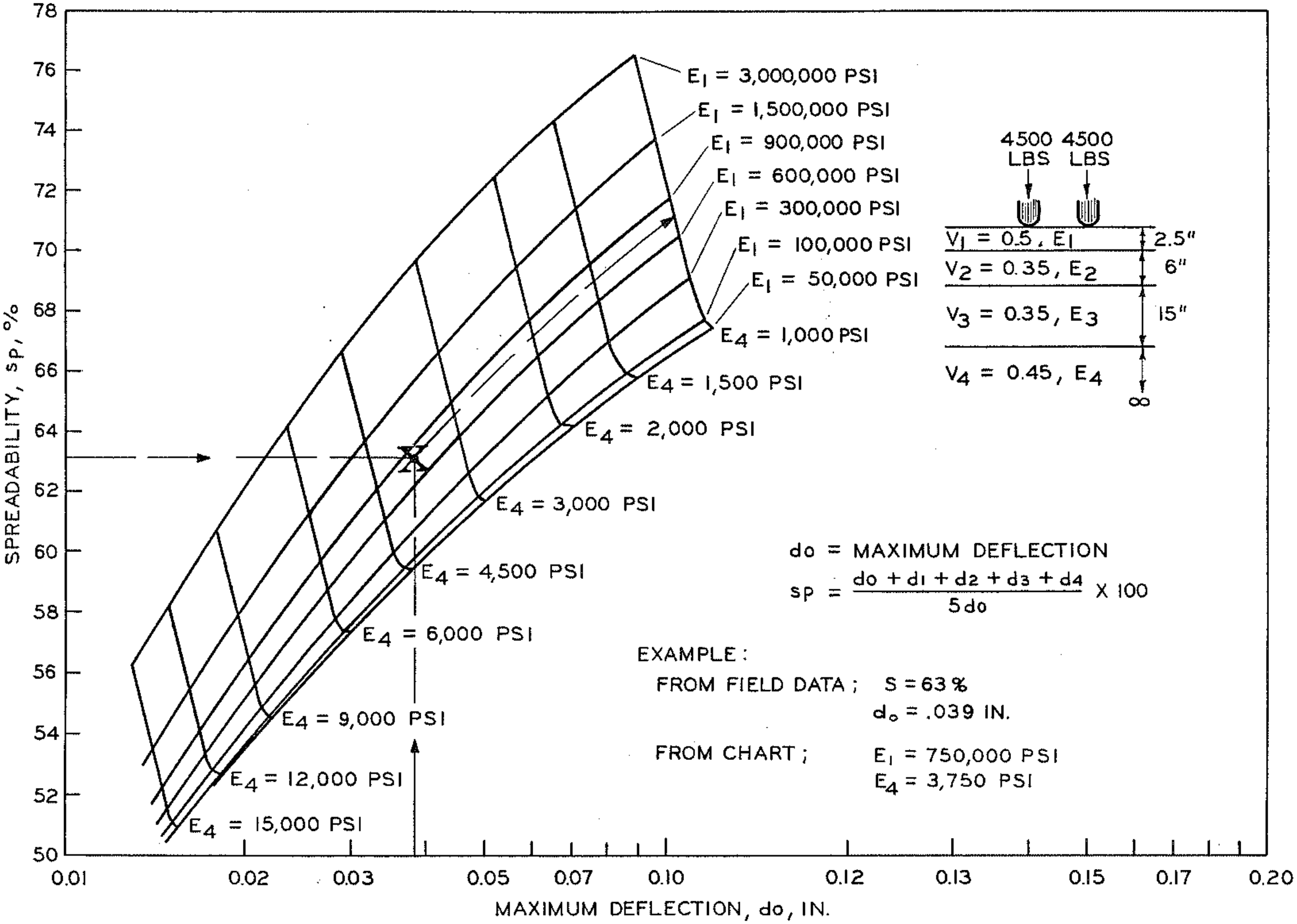


Figure 4. Relationship between spreadability and maximum deflection for various moduli.

As a check on the procedure, the E_1 values determined from the chart can be compared with values measured on core samples in the laboratory. Also, a deflection basin can be computed, using the moduli values just determined, and compared with the deflection basin determined from road measurements with the Benkelman beam.

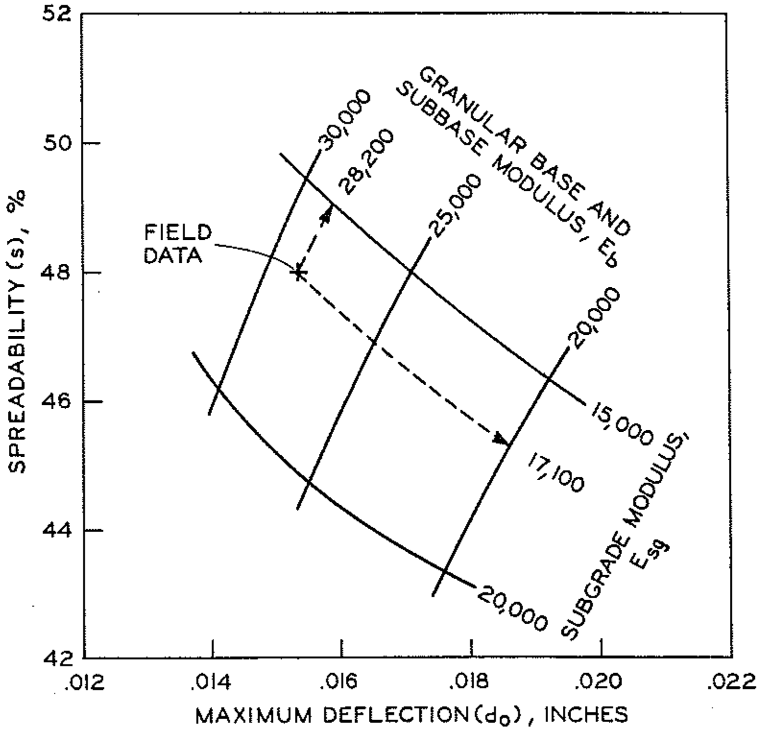


Figure 5. Relationship between spreadability, maximum deflection and moduli of subgrade and granular layers for a sulfur-extended-asphalt overlay section.

Step 3. Pavement Analysis or Design – Modulus values determined in the previous step are used in the CHEV 5L program to compute tensile strain on the bottom of the asphalt layer and compressive strains applied to the subgrade surface for fatigue and rutting considerations, respectively. For fatigue analysis or design, the horizontal tensile strain in the bottom of the asphalt surface layer is related to the number of 18-kip equivalent axle loads by the following relationship

$$N_F = 1.64 \times 10^{-7} (\epsilon_t)^{-3.67} \quad (4)$$

where: N_F = number of 18-kip equivalent axle loads (KEAL) to cause failure from fatigue

ϵ_t = tensile strain at bottom of bituminous surface for surfaces with a modulus, E_1, of 300,000 psi.

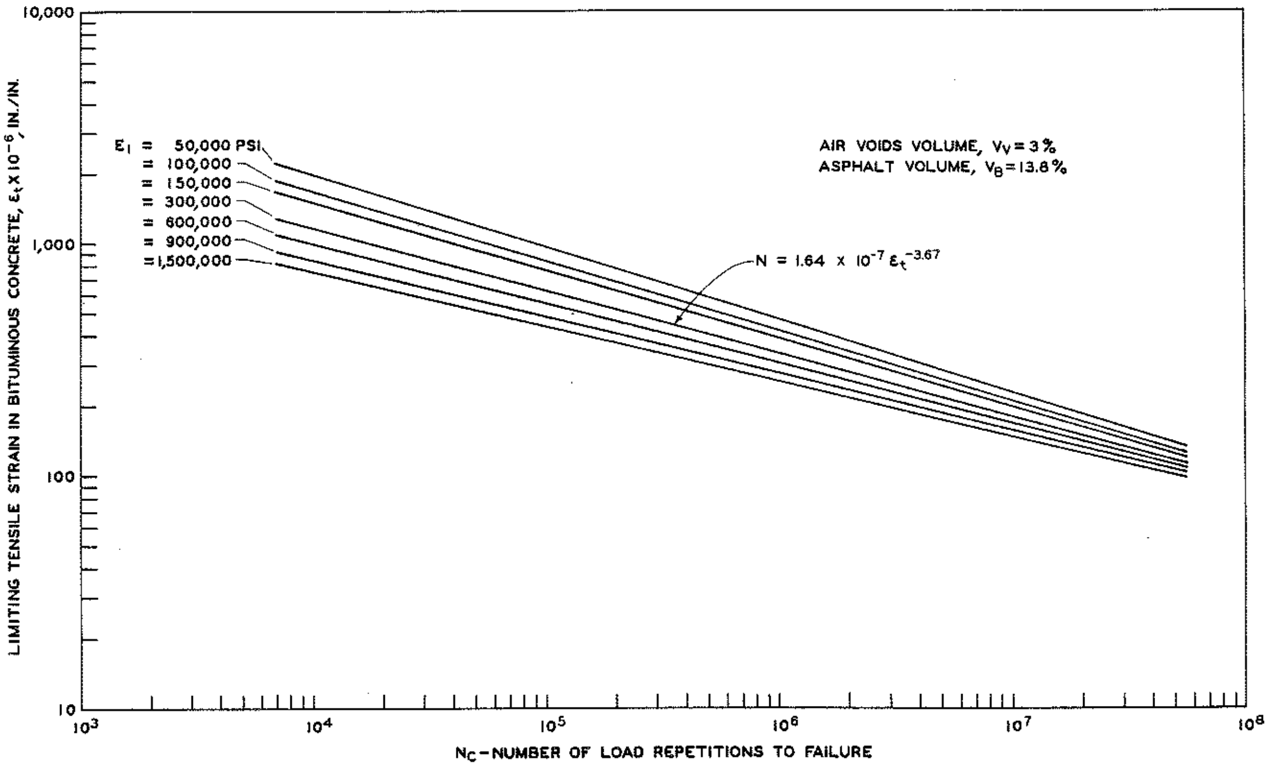


Figure 6. Fatigue criteria for a Michigan bituminous surfacing mix (from S. S. Kuo, Ref. (10)).

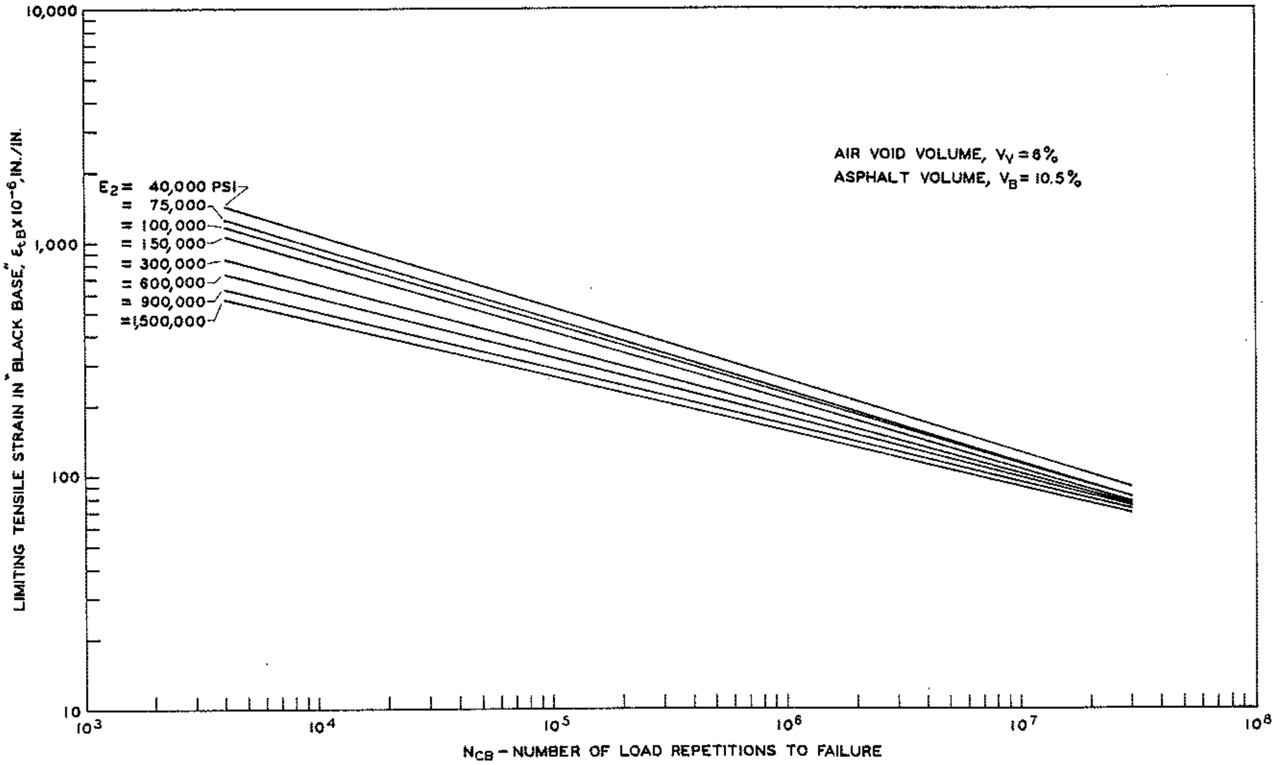


Figure 7. Fatigue criteria for Michigan asphalt-treated black base (from S. S. Kuo, Ref. (10)).

Relationships for surface courses and black base layers having other moduli are shown in Figures 6 and 7.

Rutting analysis or design is based on limiting the vertical compressive strain at the top of the subgrade with

$$N_R = 3.17 \times 10^{-9} (\epsilon_v)^{-4.37} \qquad (5)$$

where: N_R = number of 18-kip equivalent axle loads (KEAL) to cause failure from rutting

ϵ_v = compressive vertical strain on the top of the subgrade.

Figure 8 shows the relationship graphically. Pavement life is determined as the number of 18-kip equivalent axle loads to cause failure by either fatigue or rutting, whichever number is lower. The traffic count, for the specific highway, in 18 KEAL's per year can then be used to estimate the pavement life in years. The life in years is equal to the fatigue life, N_F, or the rutting life, N_R, divided by the number of 18 KEAL's/year from the traffic data.

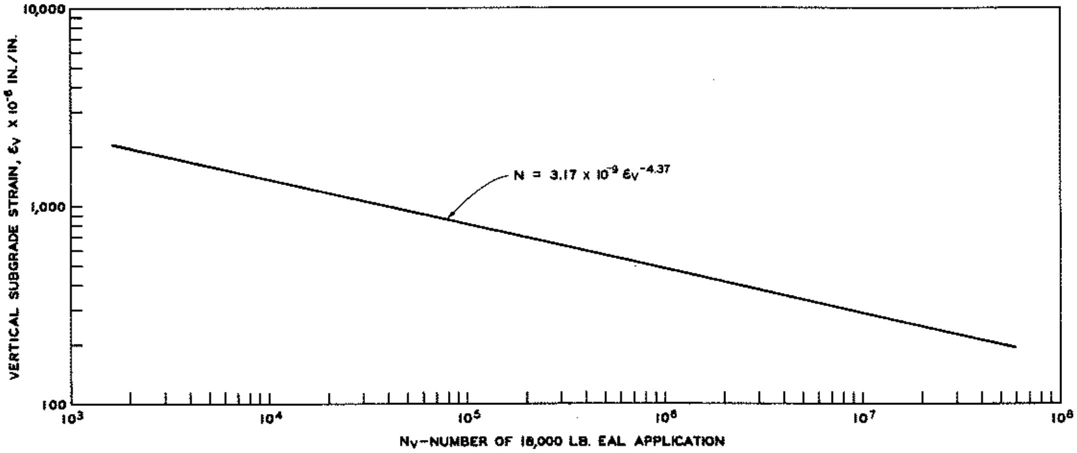


Figure 8. Effect of number of load applications on subgrade strains.

Example: Pavement Life Analysis on Sulfur-Extended-Asphalt Overlay, M 99

As part of another research project (79 D-37) an overlay of sulfur-extended-asphalt (SEA) paving mixture was placed over an existing flexible pavement (12). This pavement is analyzed as follows using the three steps outlined:

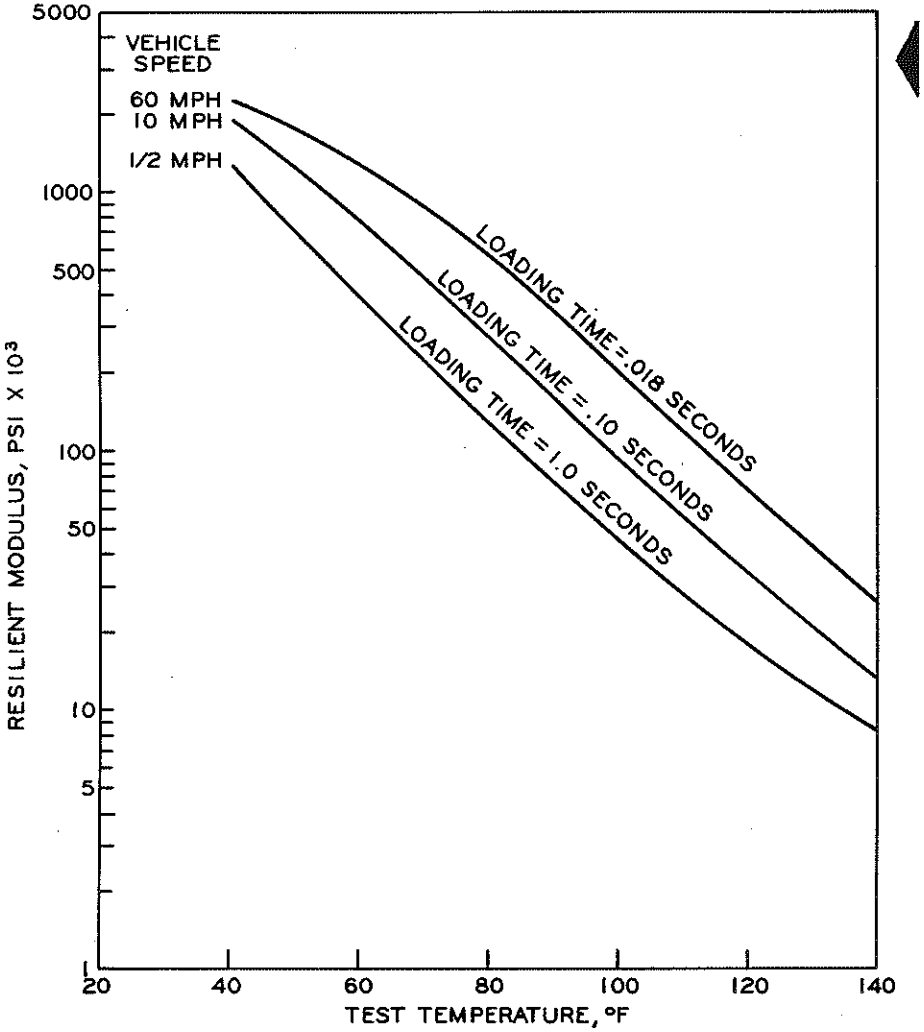


Figure 9. Relationship between stiffness modulus, temperature and loading time for SEA overlay paving mixture obtained from laboratory tests on core samples. Binder contained 30 percent sulfur and 70 percent asphalt cement 200-250 penetration.

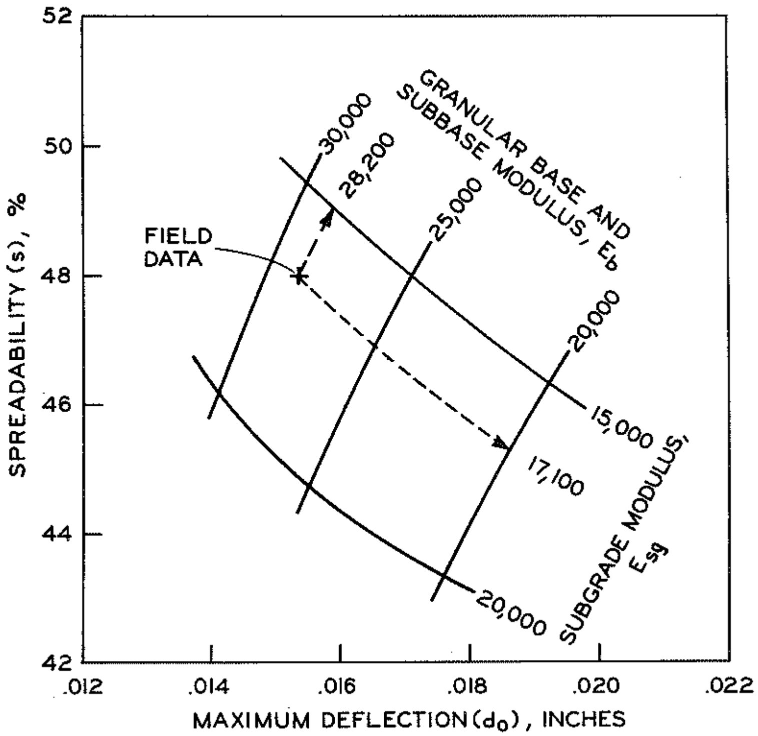


Figure 10. Relationship between spreadability, maximum deflection and moduli of subgrade and granular layers for a sulfur-extended-asphalt overlay section.

Step 1. Field Measurements — Average of values obtained at three test sites.

Pavement Cross-Section:

New overlay, SEA	$h_0 = 2$ in.
Old bituminous surface	$h_1 = 3$ in.
Aggregate base	$h_2 = 14$ in.
Sand subbase	$h_3 = 8$ in.
Subgrade	---

Deflection Basin Measurements:

Maximum deflection $d_0 = 0.0153$ in.

Distance From Load, ft	Deflection, in. x 10^2
0	1.53
1	0.98
2	0.54
3	0.36
4	0.25

Spreadability, S = 48 percent

Pavement temperature = 59 F

Step 2. Estimation of Layer Stiffness Values

a. SEA overlay stiffness, E_0, was measured in the laboratory (Fig. 8).

$$E_0 = 400{,}000 \text{ psi at 59 F and 1 sec loading time}$$

$$(1 \text{ sec} \simeq 1/2 \text{ mph vehicle speed (Fig. 9)})$$

b. Old bituminous surface stiffness, $E_1 = 70{,}000$ psi.

c. Stiffness of granular materials and subgrade – First the CHEV 5L program was used to develop a relationship between spreadability, maximum deflection and granular and subgrade moduli (solid lines in Fig. 10).

Figure 10 was computed using the layer thicknesses from Step 1 along with E_0 and E_1 values from Steps 2a and 2b, respectively.

Finally, the measured field deflection data were plotted as the point X in Figure 10 using:

Spreadability, S $= 48.0$ percent, and
Maximum deflection, $d_0 = 0.0153$ in.

Modulus values are then estimated from Figure 10, dashed lines, as

Subgrade modulus, $E_{SG} \simeq 17{,}100$ psi
Granular modulus, $E_g \simeq 28{,}200$ psi

Step 3. Pavement Life Analysis — Using the modulus values just determined, the tensile strain at the bottom of the SEA overlay and the compressive strain at the subgrade were computed:

Tensile strain, $\epsilon_t = 1.69 \times 10^{-4}$ in./in.
Compressive strain, $\epsilon_v = 1.96 \times 10^{-4}$ in./in.

Fatigue life determined from Eq. (4) or from Figure 5:

$N_F = 11.4 \times 10^6 \simeq 11$ million 18-kip equivalent axle loads (18 KEAL)

The number of axle loads to induce failure by rutting is estimated as $N_R = 50.6 \times 10^6$ 18 KEAL (Eq. 5 or Fig. 7).

As a check of the solution, i.e., to see if the moduli values estimated and used for the fatigue and rutting analyses are appropriate, the computed and measured deflection basins are compared in Figure 11. Since the two curves nearly coincide, it would seem that the values are valid.

An alternate but similar solution which matches only the maximum deflection (computed values vs. field values) can be used. Although the procedure is nearly the same as in the previous example, this method is simpler since the shape and extent of the deflection basin is not considered; only the maximum deflections are matched. This method is also simplified because the stress-dependent relationships of granular moduli are used (Eqs. 1 and 2) and their estimation is not required as part of the process.

In this alternate method, the CHEV 5L program is used to develop a relationship between maximum deflection and subgrade modulus using layer thicknesses from Step 1, granular modulus values from Eqs. (1) and (2) (Figs. 2 and 3) and surface moduli of $E_0 = 400{,}000$ and $E_1 = 70{,}000$ psi as in the previous method. Several subgrade moduli are assumed and the

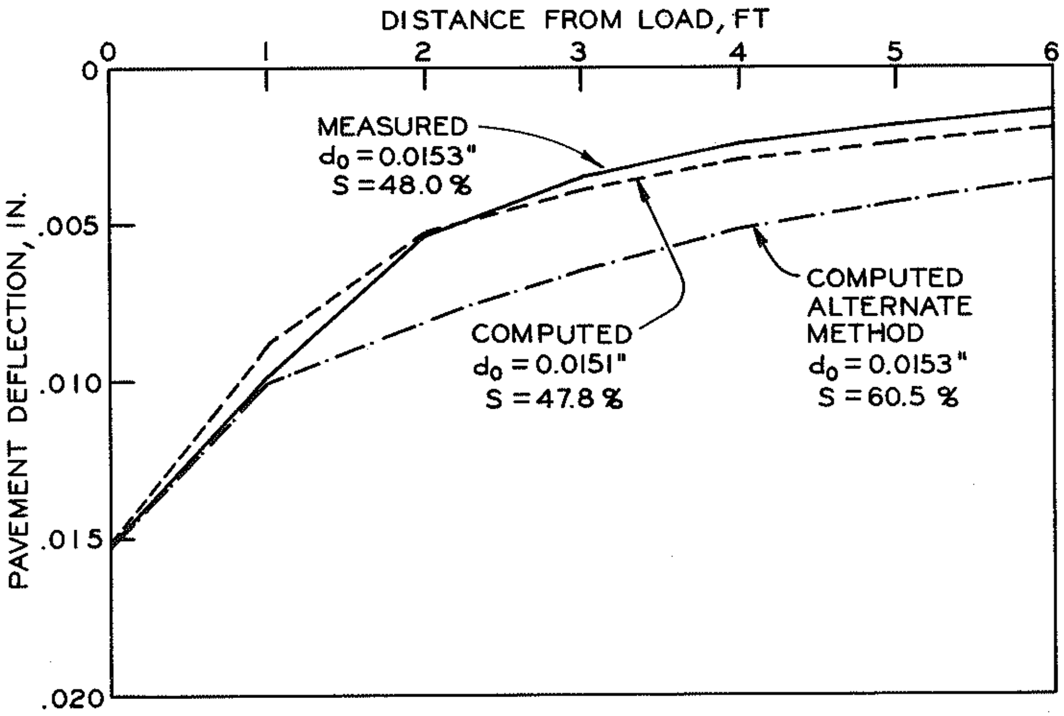


Figure 11. Comparison of measured and computed deflection basins for sulfur-extended-asphalt (SEA) overlay section, M 99.

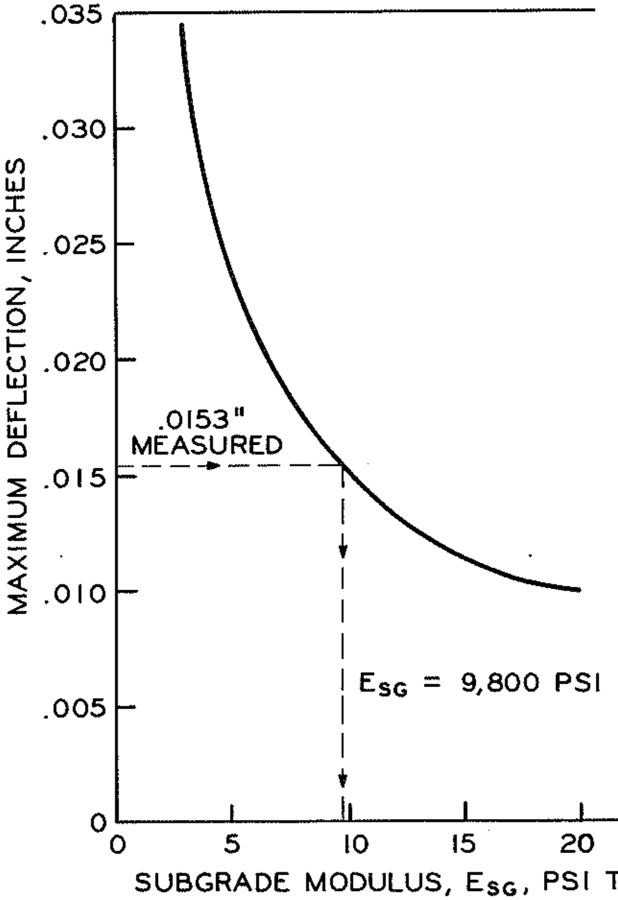


Figure 12. Relationship between maximum deflection and subgrade modulus used in the alternate method.

CHEV 5L program is used to compute the corresponding maximum deflection for each value, resulting in the relationship of Figure 12. The measured maximum deflection, 0.0153 in., thus corresponds to a subgrade modulus, E_{SG}, of 9,800 psi. Equations (1) and (2) were used to calculate granular layer moduli for each of the assumed E_{SG} values used in developing Figure 12.

TABLE 1
COMPARISON OF TWO METHODS OF DEFLECTION ANALYSIS FOR A SULFUR-EXTENDED-ASPHALT RESURFACING PROJECT

Characteristic	Measured	Deflection Basin Solution	Alternate Solution
Maximum deflection, in.	0.0153	0.0153	0.0153
Spreadability, percent	48.0	48.7	61.0
Base course modulus, psi		29,000	56,844
Subbase modulus, psi			18,240
Subgrade modulus, psi		17,000	9,800
Tensile strain, bottom of SEA overlay, ${}_t$, in./in.		1.69×10^{-4}	1.06×10^{-4}
Compressive strain, top of subgrade, ${}_v$, in./in.		1.96×10^{-4}	2.16×10^{-4}
Fatigue life, N_F, 18 KEAL's		1.1×10^{7}	6.3×10^{7}
Rutting life, N_R, 18 KEAL's		5.1×10^{7}	3.3×10^{7}

Finally, using $E_{SG} = 9,800$ and Eqs. (1) and (2), the following strain values were computed:

Tensile strain, $\epsilon_t = 1.06 \times 10^{-4}$ in./in.
Compressive strain, $\epsilon_v = 2.16 \times 10^{-4}$ in./in.

Corresponding pavement life values are:

Fatigue life, N_F = 63 million 18 KEAL
Rutting life, N_R = 33 million 18 KEAL

These two solutions are presented to illustrate methods in common use. The differences in results obtained make some comparison desirable. Table 1 summarizes results in terms of strains and predicted number of 18-kip axle loads to induce failure along with the moduli values used in each method to most closely yield predicted results. The deflection basin calculated for the alternate deflection analysis solution (based on maximum deflection only) is also shown in Figure 11 so that a comparison can be made with both the measured basin and with the basin calculated in the solution which considered the entire deflection basin.

The deflection basin method should provide a more accurate assessment of the pavement layer properties as well as a more accurate prediction of its performance than the alternate method since the computed basin was made to match, by selection of layer parameters, the measured deflection basin at all points rather than matching only the maximum deflections.

Conclusions

Methods have been developed for using deflection measurements to analyze flexible pavements and for the design of bituminous overlays over flexible pavements that are applicable to research projects where the load carrying capabilities of flexible pavement surfacings and bases must be determined.

Both the shape and magnitude of deflections measured with the Benkelman beam can be used for flexible pavement analysis and overlay design.

Methods which were presented can form the basis for more refined procedures as experience in this area of pavement analysis is developed.

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APPENDIX A

DEFLECTION TEST PROCEDURES

Scope

A procedure for determining the rebound deflection of flexible pavements under standardized axle load, tire pressure, and tire spacing is described.

Equipment

1) A load truck having an 18,000-lb rear axle load equally distributed on two wheels, each equipped with dual tires.

2) A U. S. Bureau of Public Roads type Benkelman beam such as Soiltest Model No. HT-300.

3) A direct current displacement transducer, DCDT, which measures the beam movement and replaces the dial gage normally used with the standard beam.

4) A strip chart recorder, such as Hewlett-Packard Model No. 7100B, for continuous recording of the pavement rebound.

5) A set of portable truck scales for checking the weight of the load truck.

6) Tire pressure measuring tape.

7) A 10-ft long rod marked every 1 ft, preferably made of aluminum.

8) Calibrating micrometer, suitably modified to attach to the pointer end of the Benkelman beam.

9) A three-channel thermistor thermometer, such as Cole-Parmer Model No. 8510-20, to measure air, pavement surface, and pavement temperatures.

10) A 3/8-in. masonry drill bit and suitable hand drill for drilling access holes for pavement temperature measurement.

Procedure

1) The point on the pavement to be tested is selected and marked. Points are located at the center of the outside wheelpath.

2) Check load on weight truck with portable scales and adjust to 18 kips.

3) Measure tire pressure and record on strip chart.

4) Drill a 3/8-in. hole 2 in. into the pavement near the test site and fill with lightweight oil. Place one thermistor into the hole to measure pavement temperature, another on the surface near the hole to measure surface temperature, and the other in a suitable location to measure air temperature.

5) Calibrate the strip chart recorder to the desired movement using the calibrating micrometer.

6) Locate weight truck over test site.

7) Place the pointer end of the Benkelman beam between the dual wheels so the end is located 2 in. in front of the center of the axle.

8) Loosen the locking pin on the beam and adjust the legs so that the plunger of the beam is in contact with the stem of the displacement transducer.

9) Zero the strip chart recorder, first with the rear leg of the beam and then electronically.

10) Place the 10-ft long rod beside the weight truck in the direction the truck will be moving. Locate the end of the rod 2 in. in front of the center of the rear axle, which will bring it in line with the end of the Benkelman beam.

11) With the recorder in operation, start the weight truck moving at a slow steady rate, and continue to a distance of at least 25 ft. As the center of the rear axle passes each 1 ft mark on the rod, depress event marker on the recorder. This is done every 1 ft for the first 10 ft, then every 5 ft after that, to the end of the test. The test is continued until the truck has moved 25 ft, or to a point where no more rebound is detected.

12) The operator of the recorder signals the end of the test.

13) Record on the strip chart temperatures of the air, pavement surface, and pavement 2 in. below the surface.

Calculations

The pavement rebound and distance from the load are taken directly from the strip chart recorder, thus no calculations are necessary.

APPENDIX B

ESTIMATING THE STIFFNESS MODULUS OF BITUMINOUS PAVING MIXTURES BY INDIRECT METHODS

Mixture stiffness, S_m, can be estimated from asphalt cement characteristics and mix proportions using the following nomographs and procedures. A more detailed description of methods, assumptions, and limitations is available in Ref. (13).

Scope

Van der Poel's nomograph (13), Figure B-1, along with the penetration, P, and softening point, T_{RB} (or base temperature, T_B) are used to estimate the stiffness of the asphalt cement binder, S_b, for the design loading time and temperature. The asphalt or binder stiffness, S_b, is then converted to mix stiffness, S_m, using Figure B-2 along with the known or estimated proportions of asphalt and aggregate in the mixture.

Data Needed

To estimate S_b from Figure B-1:

1) T_{RB} (T_B) °C = Softening point (base temperature) of asphalt

2) P.I. - Penetration Index of asphalt

3) T. °C = Temperature of asphalt or pavement as appropriate for test or pavement condition

4) t, sec. = Loading time appropriate for test or pavement loading.

To convert S_b to S_m using Figure B-2:

5) S_b = Asphalt stiffness from Figure B-1

6) C_v = Volume concentration of aggregate in the mix.

$$C_v = \frac{100 - \text{VMA\%}}{100 - \text{VA\%}}$$

where: VMA = voids in mineral aggregate
VA = air voids in mix.

For typical Michigan paving mixtures, $C_v = 0.88$.

Asphalt Properties, T_{RB} and P.I., Items 1 and 2

1) T_{RB} °C = Laboratory test ASTM D 2398 or AASHTO D36 or use T_B from Figure B-3 using either of the following data pairs (14):

P_4 and P_{25} where P_4 = penetration at 4 C, 200 gm, 60 sec. and
P_{25} = penetration at 25 C, 100 gm, 5 sec.

or P_4 and V_{60} where V_{60} = viscosity, poises at 60 C.

2) P.I. = From Figure B-4 using T_{RB} and P_{25} (13) or from Figure B-3 using either of the data pairs P_4 and P_{25} or P_4 and V_{60}.

For asphalts used in Michigan (15), the following values are reasonable for most estimating purposes

$$T_{RB} = 43 \text{ C}$$

$$\text{P.I.} = -1$$

Asphalt Stiffness from Van der Poel's Nomograph (Fig. 12)

Example: Assume typical Michigan asphalt cement

$$T_{RB} = 43 \text{ C}$$

$$\text{P.I.} = -1$$

Loading time, t = 0.018 sec. (60 mph)
Pavement temperature, T = 50 F = 10 C
Temperature difference = 43 - 10 = 33 C below T_{RB}

Enter nomograph with

Loading time, t = 0.02 sec. $\simeq$ 0.018
ΔT = 33 below

Read S_b at P.I. = -1

$S_b = 6 \times 10^7$ N/M^2

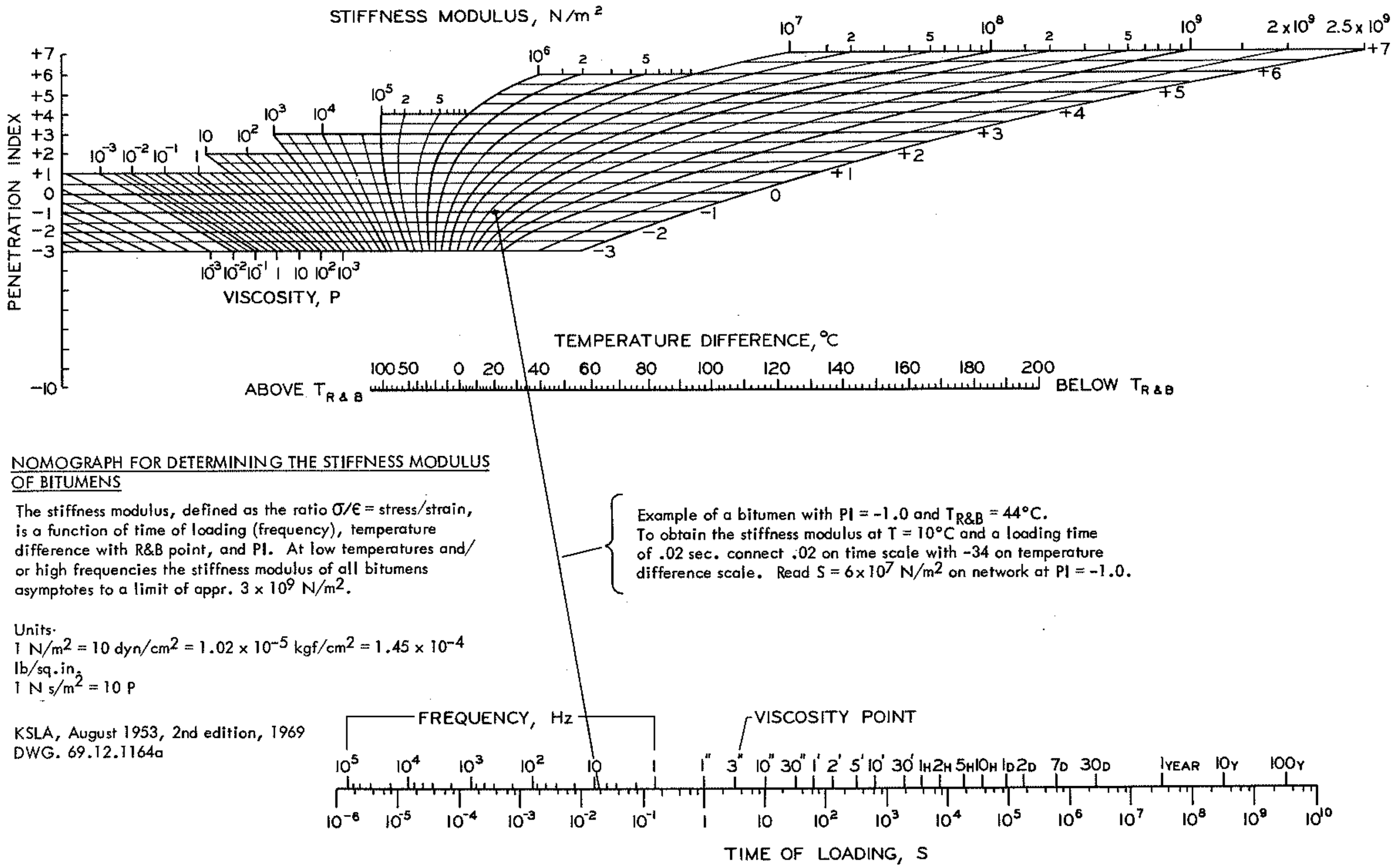
N/M$^2 = 1.45 \times 10^{-4}$ psi

Then: S_b = 8,700 psi

Bituminous Mixture Stiffness From Figure 12

1. Assume typical mix with $C_v = 0.88$
2. Enter chart with $S_b = 8.7 \times 10^3$ psi
3. Read S_m from chart using $C_v = 0.88$ curve

$$S_m = 1.6 \times 10^6 \text{ psi}$$



NOMOGRAPH FOR DETERMINING THE STIFFNESS MODULUS OF BITUMENS

The stiffness modulus, defined as the ratio σ/ϵ = stress/strain, is a function of time of loading (frequency), temperature difference with R&B point, and PI. At low temperatures and/or high frequencies the stiffness modulus of all bitumens asymptotes to a limit of appr. 3×10^9 N/m².

Units·
1 N/m² = 10 dyn/cm² = 1.02×10^{-5} kgf/cm² = 1.45×10^{-4} lb/sq.in.
1 N s/m² = 10 P

KSLA, August 1953, 2nd edition, 1969
DWG. 69.12.1164a

Example of a bitumen with PI = -1.0 and $T_{R\&B}$ = 44°C.
To obtain the stiffness modulus at T = 10°C and a loading time of .02 sec. connect .02 on time scale with -34 on temperature difference scale. Read S = 6×10^7 N/m² on network at PI = -1.0.

Figure B-1. Van der Poel's nomograph for determining stiffness modulus of bitumens (from Ref. (13)).

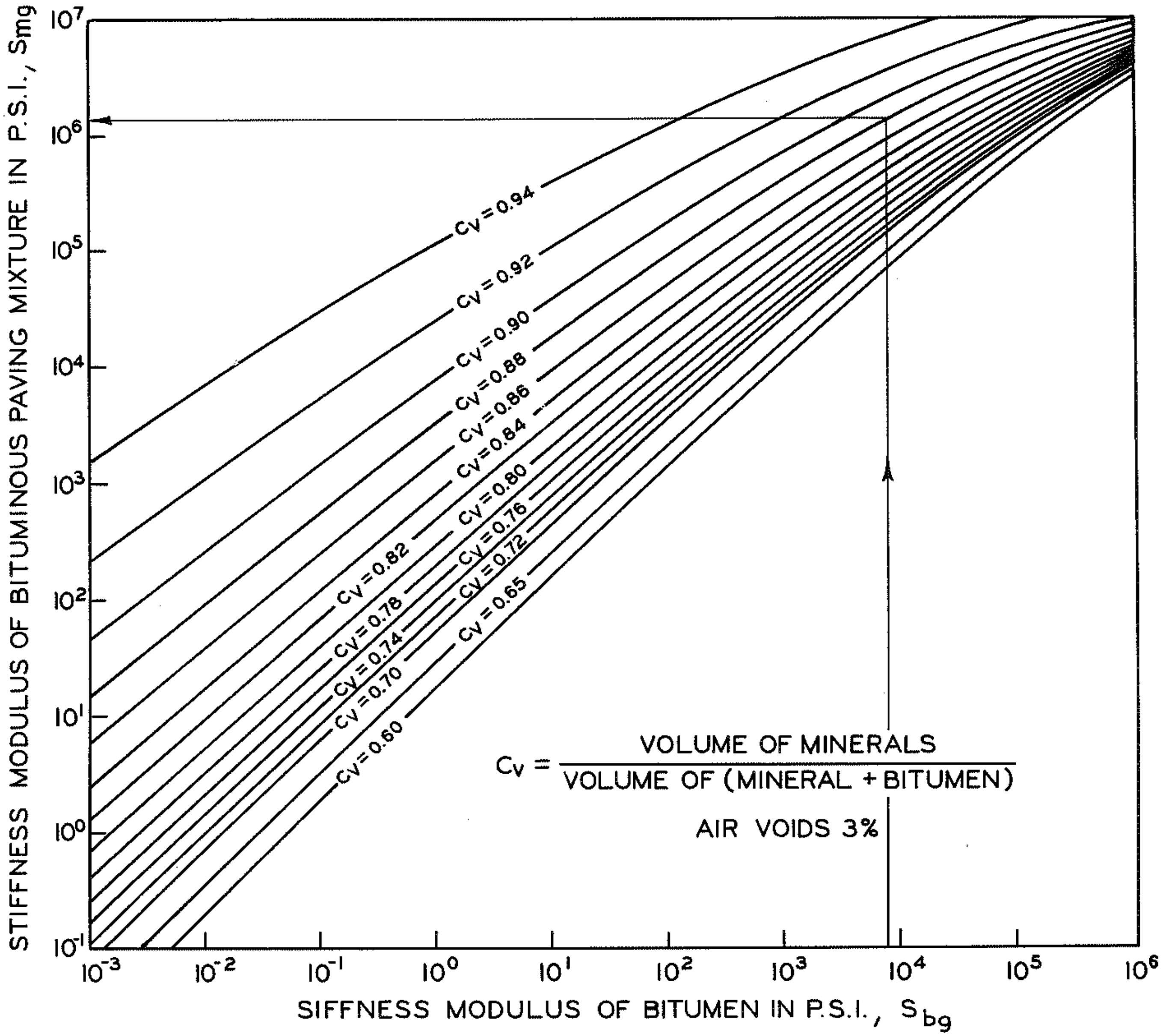
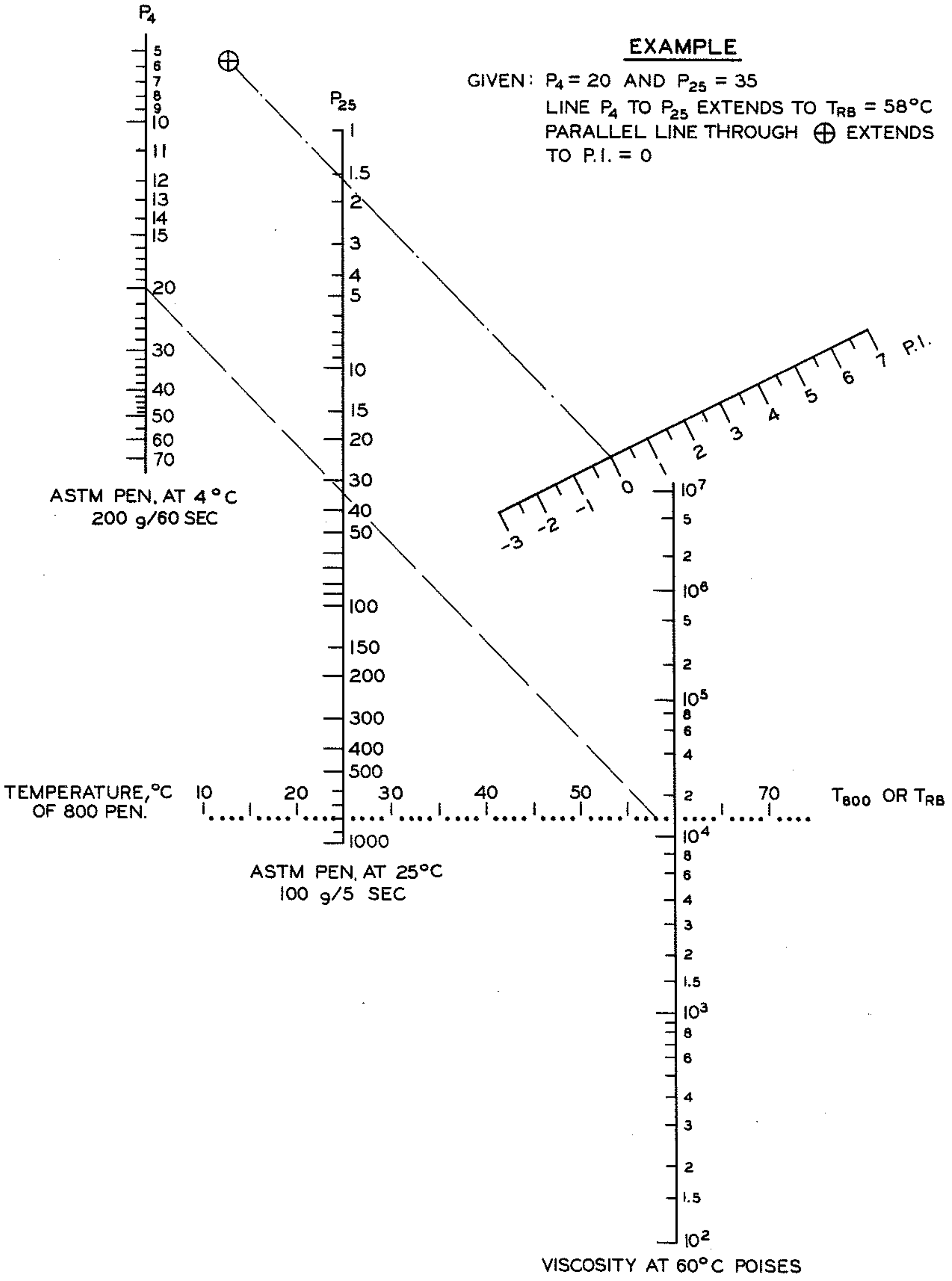


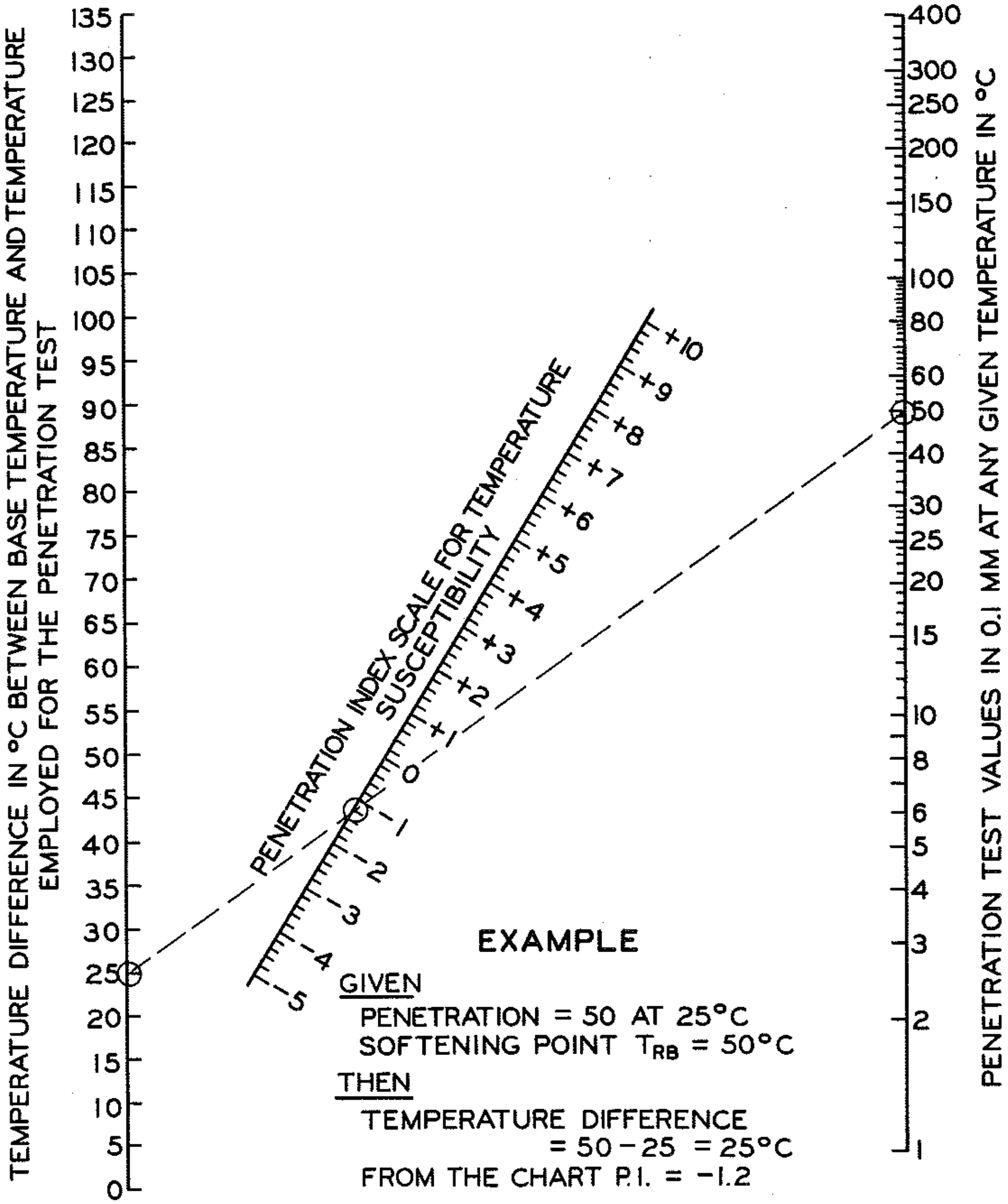
Figure B-2. Relationships between moduli of stiffness of asphalt cements and of paving mixtures containing the same asphalt cements (based on Heukelom and Klomp as presented in Ref. (13)).



EXAMPLE

GIVEN: $P_4 = 20$ AND $P_{25} = 35$
LINE P_4 TO P_{25} EXTENDS TO $T_{RB} = 58°C$
PARALLEL LINE THROUGH ⊕ EXTENDS
TO P.I. = 0

Figure B-3. Nomograph for obtaining PI and T_{800} penetration from ASTM tests (from Ref. (14)).



EXAMPLE

GIVEN

PENETRATION = 50 AT 25°C
SOFTENING POINT T_{RB} = 50°C

THEN

TEMPERATURE DIFFERENCE
= 50 − 25 = 25°C
FROM THE CHART P.I. = −1.2

Figure B-4. Relationship between penetration, Penetration Index, and softening point (13).