STRUCTURAL EVALUATION OF PAVEMENTS FOR OVERLAY DESIGN

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Agencies responsible for road construction are continually faced with upgrading existing pavements. Evaluation of pavements is far from being a standard procedure, and most highway departments are faced with adopting something already available or developing a technique suitable to their own needs. In King County, Washington, the Benkelman beam was recently adopted to systematically measure deflections. Two existing pavements in the King County network of highways were measured for deflection by using the Benkelman beam. Resilient modulus and other properties of cored samples were determined in the laboratory. These material values were used in conjunction with elastic layer theory to compute several response parameters including strain and deflection. The computed and measured deflections were compared and evaluated for compatibility. Finally, overlay requirements were determined by using the elastic layer concept and fatigue as a design life determinant. The overlay thickness determined by this method was compared to those for other techniques in current use and found to be slightly conservative.

Agencies responsible for road construction are continually faced with upgrading existing pavements. Evaluation of pavements is far from being "standardized," and many agencies are faced with many possible techniques from which to select one suitable to their needs. As one example, the Benkelman beam was recently adopted in King County, Washington, as a means of evaluating pavements for maintainance management. Intitially, the technique developed by Welch (1) was selected because it was relatively straightforward and would probably apply to this area of western Washington, which is similar to that of Vancouver, B. C.

Although the Benkelman beam appears to adequately measure rebound deflections and a number of deflection readings can be made rapidly, there are limitations to their usefulness. For example, 2 pavement sections may have identical deflections under moving wheel loads, but one may have a relatively inadequate upper structure, while the other may have a weak subgrade. It is readily evident that an infinite number of pavements may show similar deflections, but a large number of pavements may be correlated with acceptable deflection levels such as has been done in California (2). A family of curves has been developed that represent average typical asphalt concrete (AC) pavement cross sections. The tolerable deflection for a range of traffic has been correlated with acceptable performance. For the range of conditions encountered in California, these curves appear to give adequate evaluation. In effect, they also indicate approximate equivalent pavement sections based on deflection. However, it has

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been demonstrated (3) that equivalencies are very difficult to assign because each pavement has a response that depends at least on wheel load and tire pressure, thickness and characteristics of the pavement layers, and environmental factors such as temperature of the AC and moisture of the unheated materials.

If measurements on a particular pavement showed excessive deflection, it may be difficult to determine the cause; i.e., what layer contributes the largest portion of the deflection? Without adequate understanding, a pavement may be overlaid without achieving a reasonable decrease in deflection.

An attempt was made to investigate this factor more carefully by selecting 2 pavements in King County for study of deflection as related to curvature, behavior of individual material layers, and overlay requirements as indicated by theoretical computations and stress-strain considerations. Benkelman beam deflections, measured longitudinally both under the dual wheels and 18 in. away, from both sites were studied (4). Dynamic properties of each material were determined by using cores from the pavements. These values were used in elastic layer computations in an attempt to match the calculated and measured deflections. Finally, a range of overlay thicknesses was theoretically added to each existing pavement to determine the effect on deflection, strain in the AC, and strain in the subgrade.

FIELD MEASUREMENTS

This paper discusses the study of 2 of the pavements from those tested: short sections of asphalt surfaced pavements from Des Moines Way and N. E. 124th Street as shown in Figure 1.

Pavement deflections under a standard 18,000-lb axle load were measured over a length of several hundred feet. Figure 2 shows the Benkelman beam being used to measure deflection rebound after the truck has moved forward from its original position at the tip of the probe. Normally, during a deflection survey, only 2 readings are made longitudinally along the wheelpath. For the purposes of this study, however, several additional measurements were taken to describe the shape of the deflection basin. Typical maximum deflection profiles are shown in Figures 3 and 4.

Immediately following deflection measurements, the pavements were core sampled at one of the deflection measurement locations. Samples with 4-in. diameters of both the AC and the untreated (base and subgrade) layers were obtained for further study in the laboratory. Contrast between the 2 pavements was provided by 9 in. and 2½ in. of AC thickness on Des Moines Way and 124th Street respectively.

MATERIALS AND LABORATORY TESTS

A wide range of materials was found in each pavement (Table 1). The AC was originally constructed to meet state of Washington Class B requirements. Gradation of the aggregates and subgrade materials for each section is shown in Figures 5 and 6.

In addition to the usual analysis of materials, such as density, gradation, and asphalt content, the field samples were evaluated by using dynamic load conditions. Measurements were obtained that were used to compute a resilient or dynamic modulus, M_R, which is somewhat analogous to Young's modulus, E.

The resilient modulus, which can be used directly in elastic layer theoretical analysis, was obtained by using a repeated-load, triaxial testing apparatus. Original work using this method was conducted at the University of California and, with several modifications, was adopted for this study. Figure 7 shows the testing machine in operation with the triaxial cell in the left bay. Repeated loads, similar to those obtained under slow-moving vehicles, are applied by the special loading piston and through the top of the cell. A typical test sample is 8 in. high by 4 in. wide. Controls on the right (Fig. 7) are for lateral and vertical stresses, which are varied over a range typical of that experienced in actual field conditions. Both treated and untreated materials are tested in a similar manner. The response, or deformation, of the pavement materials is measured electronically by using linearly variable differential transformers (LVDT's) clamped directly to the sample as shown in Figure 8.

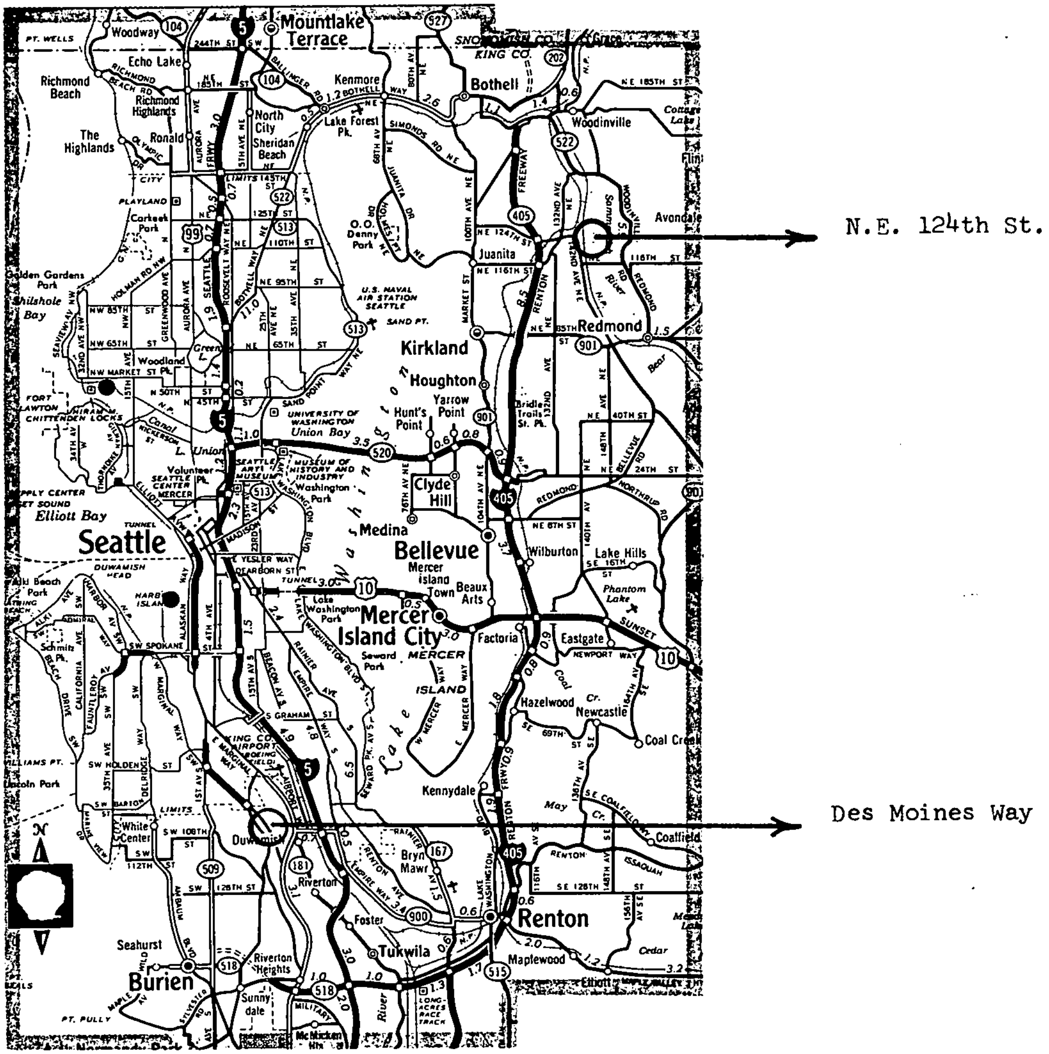

Figure 1. Location of 2 road sections.

Through calibration of load and deformation measurements, the resilient modulus can be computed as follows:

$$M_R = \frac{\sigma_d}{\epsilon_r}$$

where

σ_d = repeated deviator stress, and
ϵ_r = recoverable strain.

A range of modulus values is thus obtained depending on the rate and magnitude of applied stresses and, in the case of asphaltic materials, temperature. Figures 9 through 17 show the results of modulus tests on all materials.

Figure 2. Measurement of pavement deflection and rebound using Benkelman beam.

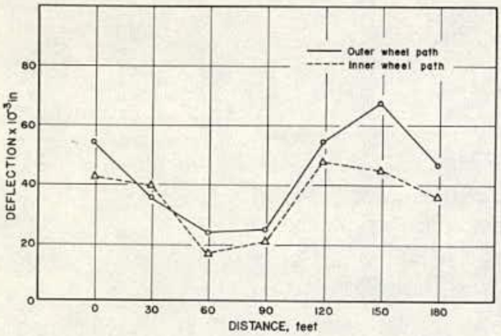

Figure 4. Deflection profile along tested section of 124th Street.

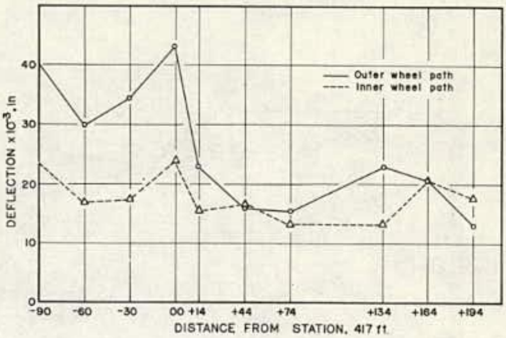

Figure 3. Deflection profile along tested section of Des Moines Way.

TABLE 1

MECHANICAL PROPERTIES OF MATERIALS TESTED

Materials	Des Moines Way	N. E. 124th St.
Asphalt concrete		
Thickness, in.	9	2.5
Penetration, dm	32	18
Softening point (R and B), deg F	123	139.8
Ductility, cm	150	99
Percentage of asphalt by weight of mix	6.4	4.8
Density of mix, pcf	137.2	
Volume concentration of aggregate, percent	80	84.4
Aggregate base		
Thickness, in.	10	5
Wet density, pcf	140	126
Water content (oven dried), percent	8.0	4.6
Water content (nuclear test), percent	13.7	
Gravel subbase		
Thickness (measured), in.		23
Thickness (required from specifications), in.		6
Wet density, pcf		140
Subgrade		
Wet density, pcf	144.5	126
Dry density, pcf	117	107
Water content, percent	19	15.3

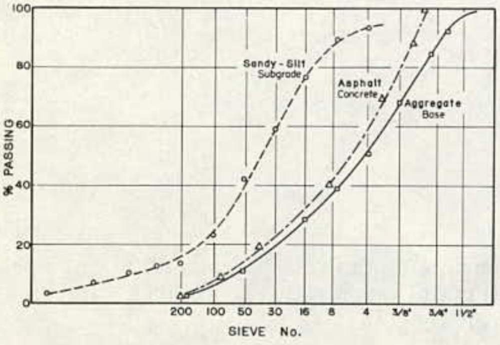

Figure 5. Grain size distribution of highway materials along Des Moines Way.

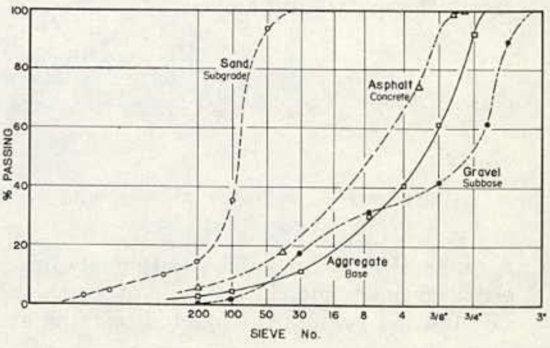

Figure 6. Grain size distribution of highway materials along 124th Street.

Figure 7. Repeated-loading apparatus with triaxial cell in place in left bay.

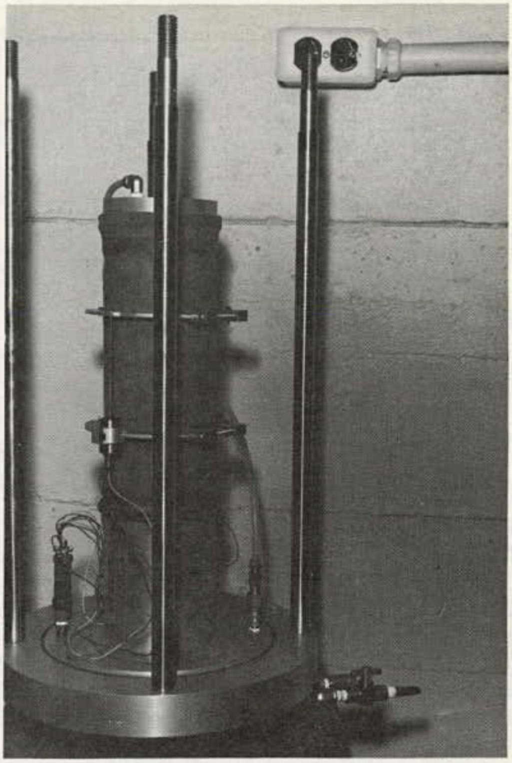

Figure 8. Two differential transformers clamped to center of sample to eliminate false readings due to end conditions (clamps were adjusted with the aid of a screw on one side and a spring on the other).

Des Moines Way

Previous work (5, 6, 7) has generally shown that the modulus of fine-grained or cohesive soils is independent of confining pressure but varies over a wide range with changing deviator stress. However, Figure 9 shows that the silty-sand subgrade is dependent on both types of stresses. Although the curves on the left in Figure 9 are similar to those usually determined for clayey soils, a separate curve exists for each confining pressure.

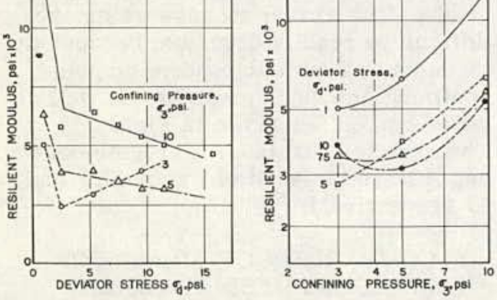

Figure 9. Effect of confining pressure and repeated deviator stress intensity on resilient modulus of Des Moines Way silty-sand subgrade.

In a similar manner, granular soils generally show little effect of deviator stress, but rather the modulus is directly dependent on confining stress (6). Although this relationship is generally true for the aggregate base in the usual range of confining stress (1 to 10 psi), extending the confining stress tends to distort the curves as shown in Figure 10. No immediate explanation is offered for this behavior.

Asphalt concrete was somewhat stress-dependent as shown in Figure 11. In this figure, 2 sets of curves are shown for different times of loading. The solid lines are for repeated load durations of 0.1 sec, as might be experienced from moving wheel

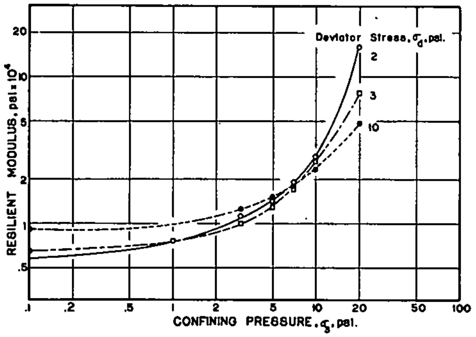

Figure 10. Effect of confining pressure and repeated deviator stress intensity on resilient modulus of Des Moines Way aggregate base.

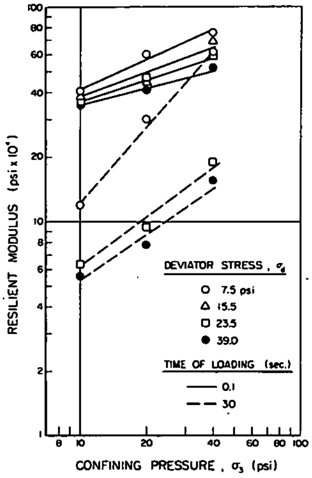

Figure 11. Effect of confining pressure, repeated deviator stress intensity, and time of load on resilient modulus of Des Moines Way asphalt concrete.

loads. For these stresses and loads, a small range of modulus or stiffness was detected. However, inasmuch as asphaltic materials are viscoelastic in nature, the slower loading rate resulted in a much wider range of modulus values with variations in stress. This longer load time was used to represent the loads experienced during the Benkelman beam deflection measurements. In another series of tests, an attempt was made to measure the effect of different stresses, including tensile or negative confining pressure. Figure 12 shows that the modulus tests were made at only one temperature. Values for other temperatures were computed as shown in Figure 13 by using the well-known Heukelom and Klomp nomograph (8). It is interesting to note that the 30-sec loading time used in the triaxial tests was more closely aligned with the 0.1-sec time curve determined from the nomograph.

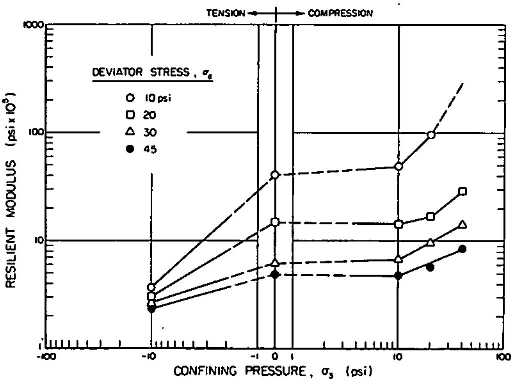

Figure 12. Effect of confining pressure and repeated deviator stress intensity on resilient modulus of Des Moines Way asphalt concrete.

124th Street

Materials found in the pavement on 124th Street were somewhat similar to those on Des Moines Way, except that a much thinner asphalt layer was used and an additional layer of subbase material was incorporated. Figure 14 shows the modulus relationships for the sandy subgrade. The gravel subbase was more difficult to readily describe, because the modulus was quite dependent on both confining and deviator stress as well as water content as shown in Figure 15. The results of tests on aggregate base and AC are included in Figures 16 and 17 respectively.

COMPARISON OF MEASURED AND COMPUTED PAVEMENT RESPONSE

A pavement structure and the individual layers that constitute it can be

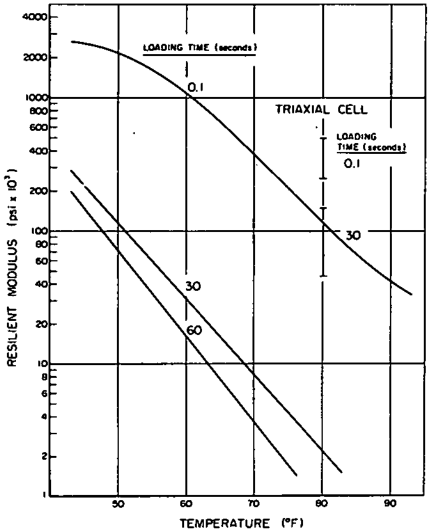

Figure 13. Effect of temperature on resilient modulus of Des Moines Way asphalt concrete as computed from Heukelom and Klomp's nomograph; results of repeated loading test superimposed at tested temperature.

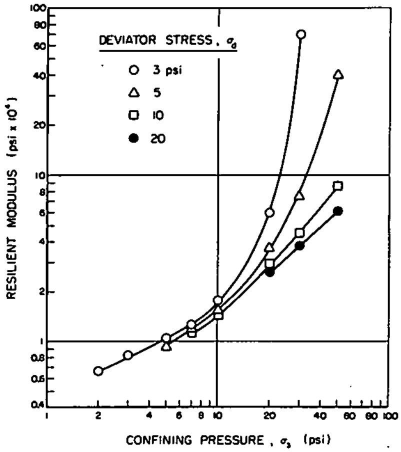

Figure 14. Effect of confining pressure and repeated deviator stress intensity on resilient modulus of 124th Street sandy subgrade.

assumed to behave elastically, at least to an engineering approximation. Elastic layer theory and its computerized version as developed by the Chevron Research Corporation can be used to calculate stress, strain, and deflections within the pavement as caused by moving wheel loads. This computer program and the appropriate modulus values for materials were used in an attempt to predict the measured field deflections. An iterative procedure was used in this investigation similar to that developed by Seed et al. (<u>9</u>) and subsequently used by others (<u>10</u>, <u>11</u>) with reasonably success. In this procedure

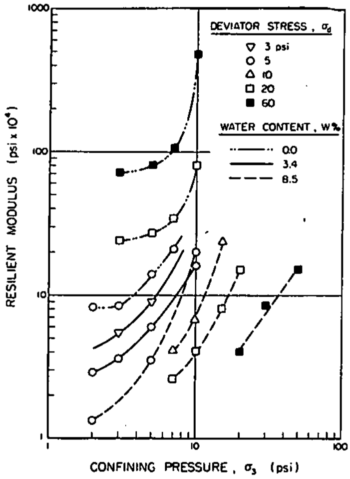

Figure 15. Effect of confining pressure, repeated deviator stress intensity, and water content on resilient modulus of 124th Street gravel subbase.

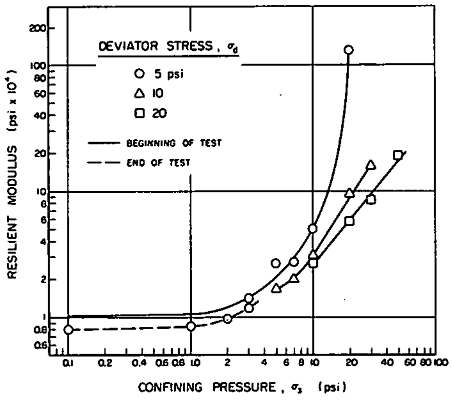

Figure 16. Effect of confining pressure and repeated deviator stress intensity on resilient modulus of 124th Street aggregate base.

appropriate estimates are made of modulus and Poisson's ratio from laboratory tests such as those shown in the previous section, and stresses and deflections are computed. From the results, new modulus values match those resulting from computations. Tables 2 and 3 give several combinations of modulus values that could represent the pavement materials at the time field deflections were measured. Once the assumed and computed values match, other parameters such as deflection can be compared. In effect, this process is a means of evaluating the validity of the theory as well as the material testing technique.

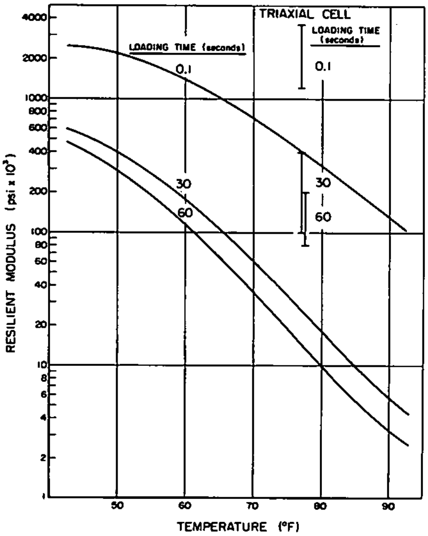

Figure 17. Effect of temperature on resilient modulus of 124th Street asphalt concrete as computed from Heukelom and Klomp's nomograph; results of repeated loading test superimposed at tested temperature.

Figures 18 and 19 show the comparison between measured and computed deflections for both roadways. The measured deflection at both the center of dual wheels and 18 in. away was compared, thus providing a basin of deflection. The dashed lines in the figures represent the results of computing deflections according to the material properties (Tables 2 and 3). By adjusting the modulus of various layers, different deflections and curvatures can be obtained. For example, in the first trial calculation for Des Moines Way as given in Table 2 and shown in Figure 18, the modulus values were relatively high. The centerline deflection was lower than measured, but the offset value was higher, indicating a relatively stiff upper layer. Because the time of loading was 30 sec in the field, a lower stiffness for the AC was selected for subsequent calculations as indicated by the laboratory tests. Ultimately, computed and measured deflections matched reasonably well but, in addition, the shape of the basin was also comparable. This factor was considered carefully because of relatively unknown conditions existing in the pavement. For example, the viscoelastic nature of asphalt mixtures tend to reduce the effective modulus

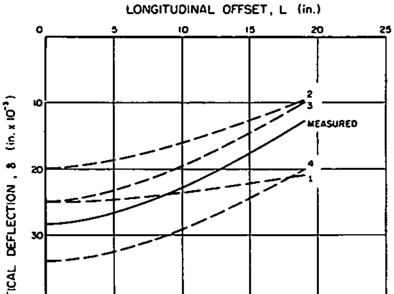

Figure 18. Comparison of calculated and measured deflection bowls along Des Moines Way.

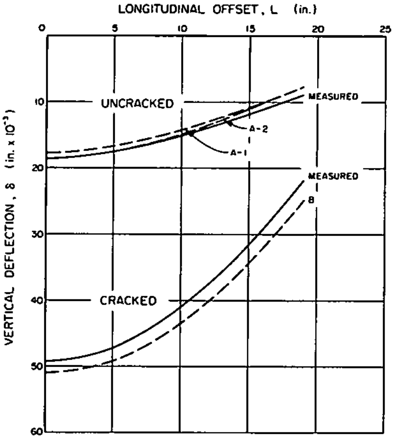

Figure 19. Comparison of calculated and measured deflection bowls of cracked and uncracked sections along 124th Street.

TABLE 2

VARIABLES USED IN THE CHEVRON N-LAYER PROGRAM TO CALCULATE THE VERTICAL DEFLECTION OF DES MOINES WAY PAVEMENT

Material Description	Cumulative Thickness of Layers (in.)	Poisson's Ratio	Resilient Modulus, psi			
			1[a]	2[a]	3[a]	4[a]
Asphalt concrete	9	0.35	520,000	117,000	80,000	80,000
Aggregate base	19	0.4	12,000	9,000	9,000	9,000
			14,000	7,000	7,000	
Sandy-silt subgrade	∞	0.45	4,000	2,000	2,000	2,000
				5,000	5,000	2,500
				100,000	100,000	10,000

[a] Numbers correspond to numbers on deflection curves shown in Figure 18.

of the layer under sustained loading because of larger deflections. Therefore, using a modulus determined in the laboratory at 0.1 sec loading time would be difficult and unrealistic in comparison to the modulus actually experienced from field measurements. Thus, subsequent computations utilized the relatively lower modulus for the AC layer.

It is interesting to note that the modulus of the thick AC layer on Des Moines Way had a significant influence on the behavior of the total pavement. On 124th Street, however, a change in the modulus of the AC was readily shown to be insignificant to the total behavior as shown in Figure 19. Although the cracking of the relatively thin asphalt surface influenced the deflection, the higher deflection of the cracked sections was found to be caused by the much thinner granular base course in these areas.

OVERLAY DESIGN REQUIREMENTS

In order for the engineer to determine the overlay requirements, if any, for pavements under study, he must have a procedure by which to evaluate their structural adequacy. The procedure used in this study was based on the strain level on the underside of the asphalt bound layer. Analysis was accomplished by using the Chevron elastic layer program and selecting a range of thicknesses for the asphalt overlay. The requirements thus derived were compared to those determined by using other procedures.

Because of the complex interrelationship among the many variables such as stress dependency of the several materials, assumptions were made that simplify the analysis without distorting the results. Analysis is limited to only the short sections of roadway under study, and the 80 percentile level of measured deflection was used. Anticipated traffic was determined for both roads according to the Washington procedure for computing equivalent 5,000-lb wheel loads as follows:

Roadway	5-Year Design Life	10-Year Design Life
Des Moines Way	350,000	715,000
N. E. 124th Street	98,300	247,500

Three thicknesses of AC overlay of 2, 4, and 6 in. were assumed for each pavement. Because the average vehicle speed for normal traffic would be much higher than that of the truck during the deflection measurements, the stiffness of the existing AC was increased to 350,000 and 700,000 psi for Des Moines Way and N. E. 124th Street respectively. The AC for the overlay was assumed to be 350,000 psi at an average annual temperature of 70 F. The resilient moduli of the untreated layers of base, subbase, and subgrade were assumed to remain the same as computed earlier (Tables 2 and 3) and did not change with increasing overlay thickness.

The vertical compressive strain on the subgrade has been used (12) as a guide in the evaluation of structural capacity. The Shell procedure suggests that a value of 6.5×10^{-4} in./in. may be a suitable limit. Inasmuch as all computed values in this analysis were well below this strain level, they were not considered critical.

TABLE 3

VARIABLES USED IN THE CHEVRON N-LAYER PROGRAM TO CALCULATE THE VERTICAL DEFLECTION OF N.E. 124TH STREET

Material Description	Cumulative Thickness of Layers (in.)	Poisson's Ratio	Resilient Modulus, psi		
			A1[a]	A2[a]	B[a]
Asphalt concrete	2.5	0.35	520,000	300,000	520,000
Aggregate base	7.5	0.4	23,000	23,000	11,000
Gravel subbase	13.5	0.4			10,000
	15.5	0.4	35,000	35,000	
	23.5	0.4	25,000	25,000	
	30.5	0.4	20,000	20,000	
	50.5	0.4	7,000	7,000	
Sandy subgrade	∞	0.4	20,000	20,000	5,000

[a] Numbers and letters correspond to those on deflection curves shown in Figure 19.

Horizontal tensile strain has been suggested by many investigators to be a useful parameter in evaluating resistance to fatigue failure. In addition, the surface deflection may be a good indicator of pavement behavior when correlated with performance. Both of these parameters have been computed and are shown in Figure 20 with respect to overlay thickness. As would be expected, both sets of values decrease with increasing thickness. The values are for points under one dual wheel of an 18,000-lb axle load.

In order to estimate a design life of each pavement (i.e., age to initial fatigue cracking), fatigue data for the AC were required. The scope of this project did not permit fatigue testing, but data from other tests were used to illustrate the method. Considerable data are available (13, 14) for fatigue, but those reported by Santucci and Schmidt (15) were used because they also included information on the properties of asphalt recovered from aged specimens that closely matched those found in this study. Figure 21 shows fatigue curves C and E, which are assumed to represent the AC of Des Moines Way and N. E. 124th Street respectively. According to the traffic expected within 5 and 10 years and the average strain experienced (Fig. 21), the overlay thickness is selected as shown in Figure 20. Recommended overlay thickness in inches of AC using elastic layer analysis is as follows:

Roadway	5-Year Design Life	10-Year Design Life
Des Moines Way	1.5	3.0
N. E. 124th Street	0.5	1.5

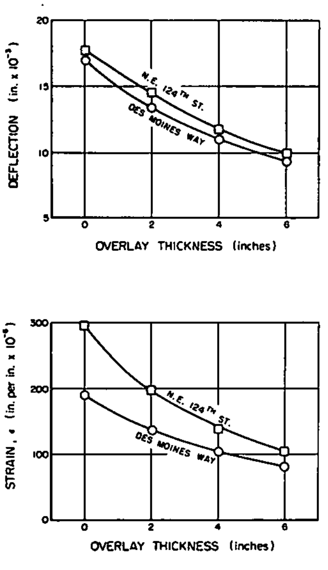

Figure 20. Surface deflection and tensile strain at bottom of asphalt layer versus overlay thickness.

Actually the existing pavements on both Des Moines Way and N. E. 124th Street should be adequate for about 3 more years under existing traffic conditions.

As a matter of interest, other overlay requirements using different procedures were considered and compared. The methods of Welch (1), California Division of Highways (2), and The Asphalt Institute (16) showed no additional pavement requirements for 5- and 10-year designs. The overlay as computed by using the layered approach does not appear unreasonable considering the parameters used. For example, fatigue data were not directly available, and assumptions using tests by others were necessary. In addition, strain on the underside of the asphalt layers was used as a criterion and, for the pavements studied, no

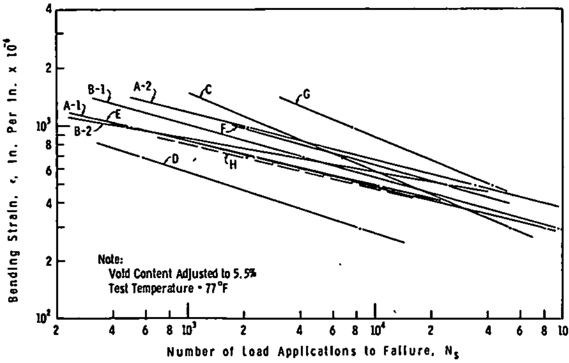

Figure 21. Fatigue response of all test mixtures aged for 7 months at 140 F (15).

surface cracking was noticeable. Thus, even with reasonably large deflections, other overlay design methods may not indicate the need for overlay if surface distress is not evident.

SUMMARY AND CONCLUSIONS

Two existing pavements in the King County, Washington, network of highways were measured for deflection by using the Benkelman beam. Resilient modulus and other properties of cored samples were determined in the laboratory. These material values were used in conjunction with elastic layer theory to compute several response parameters including strain and deflection. The computed and measured deflections were compared and evaluated for compatibility. Finally, overlay requirements were determined by using the elastic layer concept and fatigue as a design life determinant. The overlay thickness determined by this method was compared to those computed by other techniques in current use.

From the results of this study, at least the following conclusions appear to be warranted:

1. Deflection under the dual wheels as well as some distance away is a useful method of defining the deflection basin and assists in the simulation of pavement behavior for computer analysis;
2. Computed and measured deflections compare reasonably well;
3. With appropriate simplifying assumptions, overlay requirements can be estimated in a reasonably straightforward manner; and
4. Comparison of overlay requirements for the 2 roads under study show that thin overlays may be required for 5- and 10-year designs, while other available overlay methods show no additional pavement required.

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