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Use of Deflection Measurements for Determining Pavement Material Properties

B. FRANK McCULLOUGH AND ARTHUR TAUTE

This paper develops and describes models and constraints for using Dynaflect measurements to obtain the elastic-modulus inputs for layered theory. A nomograph is provided for determining the subgrade modulus of elasticity by using the sensor-1 and sensor-5 deflections. A graph and equations for correcting these modulus properties based on the thickness of the subgrade are also provided. In addition, problems associated with the modulus predictions considering stress sensitivity of pavement materials, variations of subgrade stiffness with depth, seasonal effects, and discontinuities in the pavement structure are described. A step-by-step summary procedure is provided to permit a designer to readily utilize the information presented in the body of the report.

Mechanistic design procedures require the use of a suitable theory and model to analyze the behavior of a pavement structure. Plate, layered, and finite-element theories have been used for this purpose. Typically, these theories are used to compute the tensile stresses in the upper, bound pavement layers, which are then input into a fatigue equation to predict the life of the pavement. Use of one of these theories requires that the materials that make up the pavement be suitably characterized.

Plate theory is often used for rigid pavement design; if so, the concrete layer is represented by a relatively stiff plate and the lower layers are characterized as a bed of linear springs. Elastic-layered and finite-element theories have also been used with success for rigid pavement design. These last two theories use Young's modulus and Poisson's ratio to characterize the stress-strain behavior of the pavement materials.

Taute, McCullough, and Hudson (1) have shown that plate and layered theories predict similar tensile stresses in the bottom of a concrete pavement layer when the supporting structure consists of granular material. The spring constant K used in the plate-theory calculations is equated to the layer moduli used in layered-theory calculations by computing the deflection of the subbase under a plate load with layered theory. This deflection is used to obtain the equivalent k-value of the supporting structure.

Layered-theory computer programs that can predict the state of stress, strain, and deflections of pavement structures at minimal cost are freely available. For this reason, layered theory is often used in mechanistic design procedures. Shortcomings of the theory, such as the inability to predict pavement stresses under an edge-loading condition, can be overcome by using stress-modification factors. These factors can be calculated by using plate or finite-element theories.

OBJECTIVE

Because layered-theory analysis is often used for mechanistic pavement analysis, the material properties most often required for the pavement layers are Young's modulus and Poisson's ratio. Both laboratory and in situ methods are available for determining these material characteristics. The objective of this paper is to develop and describe the techniques, models, and constraints involved in using deflection measurements to obtain the inputs to layered theory.

DEFLECTION MEASUREMENTS

The use of deflection measurements for the estimation of pavement layer stiffnesses is rapidly gaining popularity and application. Computer programs that model the pavement layers as homogeneous, isotropic, elastic layers provide reasonable estimates of pavement behavior under loading. A Dynaflect is at present used in Texas to obtain pavement deflection measurements. Thus, the developments in this paper are based on Dynaflect loadings, but the concepts are applicable to any deflection-measuring device.

The Dynaflect uses two masses rotating in opposite directions to apply a cyclic load to the pavement surface. The cycle frequency used is typically 8 Hz and the peak-to-peak load applied is 1000 lb on two steel load wheels placed at 20-in centers. The peak-to-peak deflections are measured by five geophones at 1-ft intervals; the first one is placed

Figure 1. Effect of layer moduli on Dynaflect deflection basins for typical rigid pavement structure.

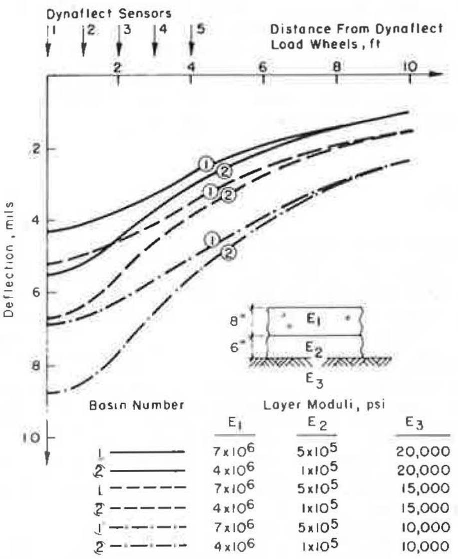
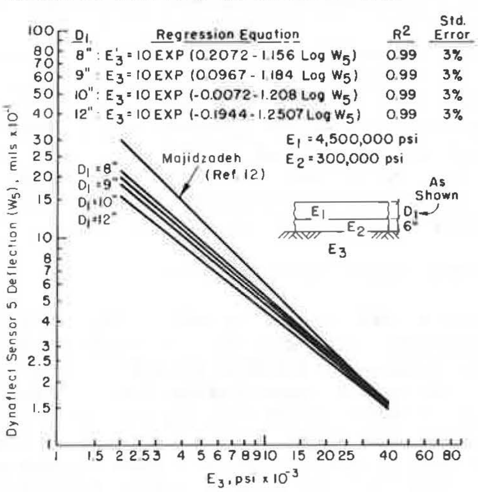


Figure 2. Relationship between Dynaflect sensor-5 modulus and subgrade modulus for different rigid pavement thicknesses.



directly between the wheels. This device thus provides an indication of the displacement and shape of the deflected surface within 4 ft of the load wheels. In the following sections, procedures for estimating material properties from Dynaflect deflections and problems associated with these predictions are discussed.

Estimation of Material Properties from Dynaflect Deflections

The pavement layer stiffnesses may be estimated from Dynaflect deflection measurements by using elastic-layered theory as follows:

1. Pavement layer thicknesses, initial estimates of the pavement layer moduli, and the loading and deflection measurement configuration are input into the computer program.
2. The computed deflections at the five geophone positions can be compared with those actually measured in the field.
3. The layer moduli used in the computer program can now be adjusted to improve the fit of the predicted and actual deflection basins.
4. This process is repeated until the two deflection basins are virtually the same. The process may have to be repeated several times before a reasonable fit is obtained.

Knowledge of the effects of changes to the various layer moduli on the shape and position of the deflection basin may speed the process considerably. Some of the terms commonly used with deflection basins are as follows:

1. Sensor-i deflection, Wi;
2. Surface curvature index (SCI), W1-W2;
3. Base curvature index (BCI), W4-W5;
4. Spreadability, (W1 + W2 + W3 + W4 + W5)/5W1; and
5. Slope of the deflection basin, W1-W5.

These parameters are related to the stiffness of one or more of the pavement layers in varying degrees. This factor is illustrated in Figure 1, in which deflection basins predicted by layered theory for different layer moduli are presented. Typical concrete pavement structures consist of a concrete pavement layer, a stabilized subbase layer, and a subgrade.

A large number of layered-theory computations were made by using this type of pavement structure, and the following conclusions have been drawn:

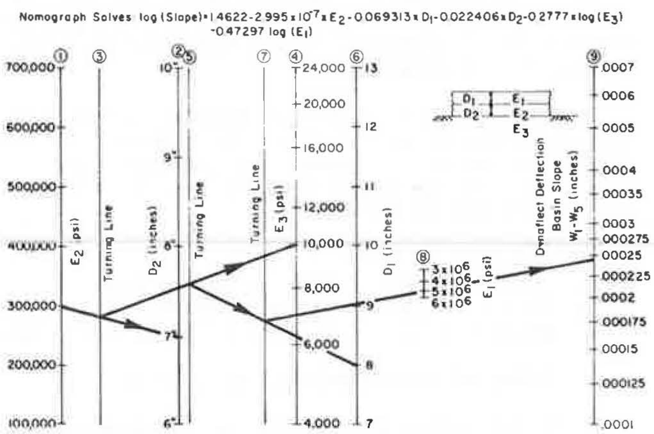
1. As illustrated in Figure 1, changes to the surface or stabilized subbase modulus result in significant changes to the sensor-1 deflections and only minor changes to sensor-5 deflections. These correspond to a change in the deflection basin slope.
2. Changes to the subgrade moduli result in significant changes to both sensor-1 and sensor-5 deflections. Both these deflection parameters are affected approximately proportionally by changes to the subgrade modulus, and there is little change to the deflection basin slope.

Therefore, it can be hypothesized with the use of interior measurements on a concrete pavement that the subgrade modulus may be predicted from the deflection at any sensor and that the slope of the basin may be used to predict the surface and subbase moduli. However, the prediction of the subgrade modulus from the sensor-5 deflection will be fairly accurate for a wide range of surface and subbase moduli because of the small effect that these moduli have on this deflection parameter. In the case of the basin slope, however, an infinite number of combinations of surface and stabilized subbase moduli exist that, when used in layered-theory analysis, will predict approximately the same basin slope.

A number of figures have been prepared to simplify the calculation of layer moduli from Dynaflect deflections. Because the pavement stiffness has a minor effect on the fifth sensor deflection, Figure 2 shows the subgrade modulus as a function of sensor-5 deflection and the rigid pavement thickness. Both the layer modulus and the thickness of the layer affect the stiffness of the layer, but the latter variable is much more important.

The relationship in the figure was obtained by regression analysis of data obtained from layered-theory computations. In the log-log form presented in Figure 2 and for constant upper-layer moduli and thicknesses, the subgrade modulus is very highly correlated to deflection at any point on the pavement surface. The regression equations used in Figure 2 and their correlation coefficients and standard errors are shown on the figure. With these

Figure 3. Nomograph for predicting Dynaflect deflection basin slope (W_1 - W_5) for rigid pavements.



equations, the subgrade modulus may be estimated with the sensor-5 reading.

The upper-layer moduli-deflection basin slope relationships may be developed for different subgrade moduli for typical conditions by using numerous layered-theory computations. From such a study it was noted that a number of combinations of surface and subbase modulus values can result in a given basin slope.

A nomograph has also been prepared for trial-and-error calculations of deflection-basin slopes from estimates of layer moduli. The equation used for the development of the nomograph in Figure 3 was obtained from regression analysis of layered-theory results. The correlation coefficient of this equation is 0.98 and the standard error of the residuals is 8 percent.

The upper-layer thicknesses and estimates of the layer moduli are used in the nomograph to obtain a prediction of the deflection basin slope under a Dynaflect load. The selected moduli can be modified until the basin slope obtained in the nomograph coincides with the slope obtained in the field. The numbers above each scale on the nomograph indicate the sequence at which the lines should be crossed. From the nomograph, it is apparent that the basin slope is extremely sensitive to surface and subbase layer thicknesses and moduli. Thus, whenever possible, laboratory testing should be used to corroborate moduli obtained from this procedure.

In the past, the surface curvature index (SCI) has often been correlated to layer stiffnesses for asphalt pavements (2). As shown in Figure 1, a typical deflection basin for rigid pavements is very flat with a large radius of curvature. Thus, for rigid pavements, the SCI is a very small quantity and any small measurement inaccuracies in the Dynaflect may result in a considerable change in SCI. This may be the cause of the larger average coefficient of variation of the SCI (50 percent) than of the basin slope (30 percent), as found in numerous field studies (1). For this reason, the slope of the basin (sensor 1 minus sensor 5) has been correlated to the upper layer stiffnesses rather than to SCI.

Problems Associated With Predictions of Deflection Modulus

A number of factors exist that may result in inaccurate predictions of moduli from deflection measurements: (a) stress sensitivity of pavement materials, (b) variation of subgrade stiffness with depth, (c) seasonal effects, and (d) discontinuities in the pavement structure. All these factors lead to significant changes in the deflection measurements and consequently to the moduli predicted from these deflections. If these problems are recognized, deflection measurements or calculated moduli can be adjusted to account for them. In the following paragraphs, methods of accounting for these problems are discussed.

Stress Sensitivity

The fact that pavement materials do not behave in a linear-elastic fashion has long been established. In May 1962 at the St. Louis conference on the AASHO Road Test (3), data were presented that showed that deflections were not proportional to load. In the discussions that followed, Hveem stated that deflection-load relationships depended on the nature of the subgrade soil. Subsequent resilient-modulus tests of subgrade soils have shown that the stress-strain relationship depends to a large degree on soil type (4,5). Most pavement materials are not linearly elastic and the moduli may vary with stress. Clayey soils may be stress softening (i.e., result in reduced modulus with increased stress), whereas granular materials may be stress hardening (have increased modulus with increased stress). The Texas overlay design procedure takes only the stress sensitivity of the subgrade into account by using the slope of the resilient modulus--principal stress difference line.

Dynaflect deflections do not provide any indication of the stress sensitivity of the pavement material. Deflection devices that are capable of applying different loads to the pavement may provide some indication of the stress sensitivity of the material. Generally, at this stage of development, an indication of the stress sensitivity of the subgrade is obtained from resilient-modulus tests.

Variation of Subgrade Stiffness With Depth

Deflection measurements provide an indication of the pavement's response to loading. Layered-theory modeling of the pavement structure typically assumes that the subgrade has a semiinfinite depth. Very little of the pavement deflection is due to compression of the surface layers; it is due mostly to compression of the subgrade. For the same subgrade stiffness, loading an infinitely thick subgrade would result in much larger deflections than loading a shallow subgrade supported by a more rigid foundation. This factor is illustrated in Figure 4, in which a number of deflection basins obtained by using the BISAR and ELSYM5 elastic-layered theory programs are plotted. The structures used as inputs to the program are indicated in the figure.

This indicates that if samples of the subgrade from immediately below the subbase layer are tested for modulus, use of this modulus in layered-theory computations with an infinite subgrade depth will overpredict the surface deflections. McCullough has demonstrated this (6); computed deflections by using moduli from material tests as inputs were greater than the field deflections. In reality, infinitely thick subgrades and homogeneous subgrades with a well-defined depth supported by a rigid foundation seldom exist in the field.

Field conditions will most often be somewhere between these two extremes. A granular subgrade whose stiffness gradually increases with depth or a clayey subgrade that, due to desication, may be stiffer at the surface than lower down may be more likely to occur in practice. Furthermore, this condition may change along the length of the road.

Figure 4. Deflection basins obtained from ELSYM5 and BISAR for two different loads and subgrade thicknesses.

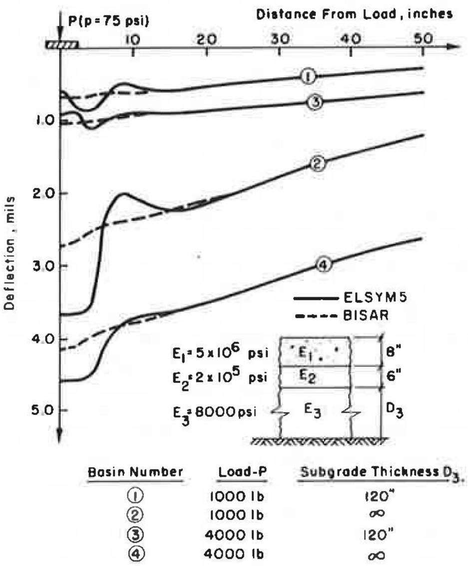
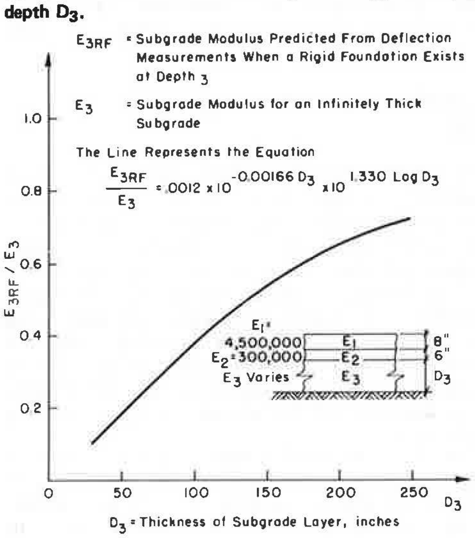


Figure 5. Reduction in subgrade modulus predicted by using Dynaflect measurements at sensor 5 when subgrade is supported by rigid foundation at depth D_3.



Cut-and-fill areas, for example, may have extremely different subgrades. Seismic testing or deep probing may provide some information to the designer in this regard. If no information is available, engineering judgment should be used for an approximation of the change in subgrade stiffness with depth.

Furthermore, from Figure 4 it is apparent that layered-theory programs, such as ELSYM5, that are based on the CHEVRON 5 program predict unrealistic deflections in the vicinity of the load. For predictions of Dynaflect deflections by using ELSYM5 or a similar layered-theory program, these discontinuities are significant in the case of a subgrade supported by a rigid foundation because the first sensor is 10 in away from the loading point and thus is above an irregular deflection as predicted by these programs. Therefore, if the deflection measurements are made near the loading point, BISAR should be used to compute fitted deflection basins.

These factors need to be considered when subgrade moduli are predicted from deflection measurements, and, to this end, Figure 5 has been prepared. This figure was produced from regression analysis of the results of layered-theory computations of the behavior of typical existing pavement structures. It shows the relationship between the thickness of the subgrade layer and the ratio of the subgrade modulus predicted from sensor-5 Dynaflect deflections for a semiinfinite subgrade depth and the subgrade modulus predicted from the same deflection measurement if a rigid foundation exists at some depth.

The figure was obtained as follows:

1. Numerous layered-theory computations of the deflections at sensor 5 under the Dynaflect load were made.
2. A regression equation describing the subgrade modulus as a function of the sensor-5 deflection and the depth to the rigid foundation was obtained. This equation is as follows:

$$E_R = 10\exp(-1.3832 - 0.0016\ 584 \cdot D_3 + 0.6394 \cdot \log D_3 - 0.7582 \cdot \log W5 - 0.2034 \cdot \log D_3 \cdot \log W5) \quad (1)$$

where

E_R = subgrade modulus as predicted by layered theory from deflections when a soft subgrade is supported by a rigid foundation,
W_5 = sensor-5 Dynaflect deflection, and
D_3 = thickness of the soft subgrade layer (in).

3. Equation 1 was the ratio divided by the equations presented in Figure 2 for the same pavement structure and an infinitely thick subgrade and then reduced to the following by fixing W_5 = 0.004 in:

$$E_R/E = 0.0011 \times 10\exp(-0.001\ 66D_3 + 1.33 \cdot \log D_3) \quad (2)$$

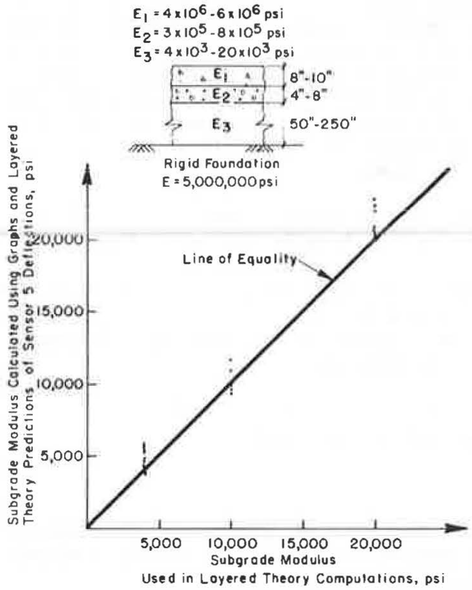
From Figure 5, it is apparent that this type of analysis may result in substantial reductions to the subgrade modulus, depending on the thickness of the soft subgrade layer. The accuracy of Equation 2 is reflected by the results presented in Figure 6. This graph was developed by making a number of random calculations by using layered theory within the ranges of layered thicknesses and moduli shown in Figure 5. Although some substantial errors may occur in the moduli predicted by using these equations, they are not significant when compared with the uncertainty regarding the actual change of subgrade modulus with depth. Figure 5 can thus be used to provide an approximate estimate of the reduction to the subgrade modulus calculated from deflections only if a rigid foundation exists. Seismic testing and engineering judgment (provided by test borings for bridge foundations, etc.) should be used to estimate whether any reduction to the subgrade modulus calculated by using deflections is required for a particular area.

Seasonal Effects

Deflections measured along the road change due to seasonal changes of moisture and temperature. With continuously reinforced concrete (CRC) pavements, changes in the environment affect the deflection measurements in two ways. Cold temperatures caused the concrete surface layer to shrink, causing an increase of the transverse crack widths. Periods of increased rainfall result in slightly higher moisture contents in the subgrade and a corresponding lower subgrade modulus. The effects of these factors on deflections have been illustrated by McCullough and Treybig (7).

First, let us consider the effect of these environmental factors on the sensor-1 Dynaflect de-

Figure 6. Comparison of subgrade modulus used in layered-theory analysis and subgrade modulus estimated by using graphs from layered-theory deflections.



flections or, in other words, on deflections near the center of the deflection basin. A wet winter will result in an increase in deflections compared with those from other seasons. This will be due to the wet, soft subgrade and the low effective modulus of the surface layer caused by shrinkage and the resulting relatively wide transverse cracks. A dry summer will result in a decrease in this deflection due to the dry stiff subgrade and the high effective surface modulus caused by expansion and the resulting narrowing of the transverse cracks in the CRC pavement. Wet summers or dry winters may not appreciably change this deflection relative to other seasons, due to the counterbalancing effects of the environment on the different layer moduli.

If, on the other hand, the sensor-5 Dynaflect deflection and the slope of the deflection basin are considered, environmental factors that affect the subgrade and surface may be distinguishable. Moisture effects on the subgrade should affect the sensor-5 deflection, and temperature effects on the surface should affect the basin slopes.

Therefore, if laboratory testing can be done to determine the moduli of the surface and subbase layers, deflection measurements should be made during the wettest season of the year to obtain the most critical subgrade modulus from these measurements.

Discontinuities in Pavement Structure

Cracks in the rigid pavement layer may have an effect on deflections if some loss of load transfer is caused by the cracks. With CRC pavements, the cracks are tightly closed, which results in very little loss of load transfer. As explained, a drop in temperature can cause these cracks to open; thus some loss of load transfer may result. This will cause an increase in the sensor-1 deflection with a corresponding change in basin slope and the moduli predicted from this deflection parameter. The effect of these cracks on stresses in the concrete layer has been discussed in more detail (1).

VARIATION IN PAVEMENT LAYER STIFFNESSES

Stresses in the upper pavement layers resulting from heavy axle loads will be affected by variation of the pavement layer stiffnesses. The layer stiffnesses are in turn affected by variations in layer thickness and modulus. These material stiffnesses may vary in both the horizontal and vertical planes. Different pavement layers will have different amounts of variation associated with them.

Effect of Varying Layer Stiffnesses on Stresses in Pavement

Before the variations associated with each layer's stiffness are discussed, it is useful to know what effect a change in a specific layer stiffness will have on the tensile stresses in the design layers of the pavement. (The design layers of a pavement are defined as those layers calculated to last the design life of the pavement, based on fatigue.) This is shown in a study made by using a typical three-layered pavement structure by varying the layer moduli. From the study, it is apparent that decreasing subbase and subgrade moduli results in an increase of the tensile stresses in the surface layer under load. Increasing surface modulus also increases this critical stress. The effect of changing layer thickness on the critical tensile stress in the pavement is difficult to quantify. For example, very thin pavement layers may have no tensile stresses in them under load. It is sufficient to say that, within the range of thicknesses typical of CRC pavements, an increase in layer thickness will decrease the tensile stresses in the rigid pavement layer.

Methods of Accounting for Variations in Layer Stiffnesses

One of the best methods for obtaining an idea of the amount of variation in the layer stiffnesses along the length of a road is with deflection measurements taken at fixed intervals along the road. The measurements are then plotted to provide a visual indication of the variation. This method has the advantages of economy and speed over material sampling and laboratory testing. If stage construction is used, the method can be applied equally well to the compacted subgrade of the pavement under construction and to the surface of an existing pavement in need of rehabilitation.

The variation in layer stiffnesses can be divided into two groups: random variation and stratified variation. Random variation is present in all pavement materials and structures. It is normal and due to the heterogeneous nature of the pavement layers. This variation is often reflected in the deflection measurements by some scatter among the results for a section of roadway. Stratified or assignable variation occurs due to a significant change in factors such as layer stiffnesses or thicknesses. For example, the subgrade stiffness in a cut or fill area may be slightly different. If possible, the stratified variations should be accounted for by separating design sections with assignable differences. This is not always practical; for example, if an area of a certain weak subgrade type is small, it may be included within a larger adjacent section and its variation added to the random variation of the larger section. The random variation may, for example, be accounted for by designing for a deflection based on a certain statistical confidence limit (8,9).

AREAL VARIATIONS

A major consideration in selecting material properties for pavement analysis is the variation of properties along the road. Thus, one must select the design sectors considering this variation, but the length must be responsible and practical.

Selection of Design Sections

A visual indication of the deflection and layer stiffness variation is provided when deflection measurements are plotted to scale as a function of distance. The PLOT program, documented by Schnitter, Hudson, and McCullough (9), provides a plot of deflections by means of a computer line printer. This plot facilitates dividing the roadway into sections based on stratified variation of deflection data. Previously, deflection sections have been selected based only on sensor-1 deflections. Now that layer stiffnesses may be predicted from deflection measurements, as described previously, sections may be selected based on the sensor-5 deflections and the slopes of the deflection basins. The sensor-5 deflection is used to select sections with different subgrade stiffnesses and the basin slopes are used to select sections with different effective surface stiffnesses. Sections are selected subjectively based on a plotted profile of these deflection parameters.

When design sections are selected, each section that represents a change in sensor-5 deflection should also represent a change in the sensor-1 minus sensor-5 deflection parameter, but not vice versa. This is because the subgrade modulus does have a significant effect on the basin slope, but the surface stiffness does not have a significant effect on the sensor-5 deflection.

Furthermore, implementation of the overlay design procedure (RPOD2) has shown that changes in deflection variance are as important as the changes in the mean deflection in the selection of design sections. Areas with similar mean sensor-5 deflections but with significantly different variation thereof should be separated into different design sections.

Because sections are selected by considering two deflection parameters and their variances, this process may result in many small sections. In order to keep the number of short sections to a minimum, limits of sections selected from different deflection parameters should be made to coincide wherever possible.

After selection of different design sections, RPOD2 recommends the use of the Student's t-test to determine whether the section means are significantly different at specific confidence levels. However, one of the shortcomings of this test is that it assumes that the sections (or data) being tested have similar variances.

As indicated earlier, different sections may have different variances, and, if so, these differences are important factors in the selection of sections. This shortcoming could be overcome by using a statistical test designed for testing differences between sample variances. Before embarking on such a course, the consequences of incorrectly selecting or not selecting a section should be examined.

Section Size

As recommended above, contiguous design sections are selected based on the mean and variance of the Dynaflect sensor-5 deflections and the slope of the deflection basins. The shortest section selected should be long enough so that it is practical and important to construct a distinct set of pavement thicknesses and materials over the length of the section. Implementation of the RPOD2 design procedure has indicated that this length is approximately 1000 ft. The section should also be long enough to contain sufficient deflection measurements for the designer to make fairly accurate inferences about the section's overall behavior from this sample of deflections. If the deflection measurements are normally distributed, a statistical formula can be used to determine the sample size. If, for example, the sample mean should only have a probability α of differing from the population mean by more than d percent, then the formula is as follows (10):

$$N = (tS)^2/D^2 \quad (3)$$

where

N = sample size,
t = abscissa of normal curve that cuts off area α at tails,
S = standard deviation of the population, and
D = dy where y is sample mean.

Implementation of the RPOD2 design procedure has shown that a typical value for S of the sensor-5 deflection is 0.10 mil. The sensor-5 deflection depends on the subgrade modulus and typically varies from 0.2 mil to 0.5 mil. A value of 0.3 mil can be used as representative of a fairly good subgrade. Therefore, if α = 5 percent and d = 10 percent, then

$$N = (1.96 \times 0.1)^2/(0.1 \times 0.3)^2 = 24 \quad (4)$$

This indicates that if a section length of 1000 ft is the shortest practical construction unit length, then, for these constraints on inference accuracy, deflection measurements are required at 50-ft intervals within that section. This inference accuracy becomes important when confidence limits of deflections for the different design sections are predicted.

SUMMARY

The procedure for characterizing the material properties of a pavement may be summarized as follows:

1. For a new pavement, material tests should be used to obtain an indication of the mean and variance of the layer moduli. If stage construction is used, take deflection measurements every 50 ft along the length of the prepared roadbed. Similar measurements should be taken in the event that an existing pavement needs rehabilitation. The measurements should be taken approximately 3 ft in from the outside shoulder.
2. Run the PLOT4 program by using the deflection data as input. This program will plot the profile of the W5 and W1 minus W5 deflections along the length of the road, as illustrated by Schnitter, Hudson, and McCullough (9).
3. Select contiguous sections from this plot by using the means and variances of both the plotted deflection parameters as selection criteria with a minimum length of approximately 1000 ft. To prevent having a number of short sections during the selection process, the limits of sections selected based on W5 deflection and on the basin slope measurements should be made to coincide where possible.
4. A design value should be selected based on the statistical variability and desired level of confidence.
5. The output from steps 3 and 4 may be used as a guideline for selecting sections that have similar sensor-5 deflections for obtaining core samples.
6. Obtain cores from the bound pavement layers and push-barrel samples of the subgrade layer. In

the event of a granular subgrade, in situ densities and moisture contents should be obtained and the specimens recompacted in the laboratory to simulate field conditions.

7. Conduct indirect tensile tests on the bound layers and resilient modulus tests on the unbound layers. The moduli obtained from these tests should be used as first estimates of the layer material properties. The slope of the M_R principal stress difference line should provide a reasonable estimate of the subgrade stress sensitivity.

8. Deflection basin-fitting techniques are then used to obtain the surface and subbase layer moduli. The design W5 deflection of a section is used in Figure 2 to obtain the modal subgrade modulus for the section. This modulus should be used in conjunction with the modulus estimates for the bound layers obtained from indirect tensile tests as initial input to a layered-theory program. The deflection basin slope of this structure under the Dynaflect load as predicted by layered theory is then compared with the measured basin slope of the section. The input moduli for the bound pavement layers may require adjustment, and this process is repeated until the basin slope predicted by layered theory corresponds to the basin slope. Should a computer not be readily available, Figure 3 can be used to provide estimates of these moduli.

9. This process will provide a set of effective layer moduli that occur most frequently in the section under the Dynaflect load. In order to obtain a reasonably conservative design, a subgrade modulus representative of the weaker spots within a section should be used. The cumulative distribution curve of the sensor-5 Dynaflect deflection for the section may be used for this purpose. Depending on the design reliability required, the W5 deflection corresponding to a required percentile can be selected from the distribution curve to represent the weaker subgrade. This design deflection is now used in Figure 2 to obtain the design subgrade modulus under the Dynaflect load.

10. Should the designer have some idea of the nature of the change of subgrade modulus with depth, the design subgrade modulus should be reduced as indicated in Figure 5.

11. The final step in the materials characterization process is to take the stress sensitivity of subgrade into account. One method is to use the slope of the log resilient modulus log deviator stress line obtained from the resilient-modulus test as an indicator of the stress sensitivity. The method has been described in detail.

12. The materials characterization for the pavement structure used in layered-theory analysis is now complete.

This materials characterization is one of the most important steps of a pavement design procedure. The tensile stress in the bound pavement layers, and consequently the fatigue life of the pavement, will depend on the moduli of the layers used as inputs in layered-theory analysis.

CONCLUSIONS

The procedures described in this report provide guidelines for a designer to use Dynaflect deflections as input for developing elastic properties, i.e., layer moduli, for use with elastic-layer analysis procedures. The guidelines permit consideration of statistical variation along a roadway, variations in depth of subgrade, stress sensitivity of materials, etc. Without accounting for these conditions, a designer may arrive at properties that are erroneous, thus destroying the credibility of the design analyses.

Although the charts provided herein are applicable to Dynaflect loading, the concepts may be applied to any deflection-measuring equipment. Furthermore, stress sensitivity procedures must be accounted for with any type of measuring equipment since the load may not be the same as those using the roadway.

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