USE OF NONDESTRUCTIVE TESTING IN THE DESIGN OF OVERLAYS FOR FLEXIBLE PAVEMENTS

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ABSTRACT

This paper describes the results of a recent study conducted for the Federal Highway Administration (1). The objective of the study was to develop a ready reference describing available nondestructive testing (NDT) devices and methods for use in designing the thickness of asphalt concrete overlays for flexible pavements. The report was developed to serve as a guide to practicing highway engineers who are considering the purchase of new equipment or developing (or modifying) overlay design procedures for flexible pavements.

Selected overlay design procedures which use NDT input are reviewed. Important components related to use of NDT data with overlay design procedures are discussed. The following items and their relation to overlay design of flexible pavements using deflection data is discussed in depth: seasonal influences on the deflections, location of test points on the pavement surface, frequency of testing, need for cores and laboratory testing, type of NDT measurements (i.e. maximum deflection, basin characterization, etc.), additional field measurements that are required, corrections to NDT measurements for temperature, etc., pavement properties calculated or inferred from the NDT measurements, method used to distinguish between different design sections, relationships which are used to convert NDT measurements to design parameters, relationships which relate the design parameters to the useful life of the pavement, and the nondestructive testing devices which are available for use.

INTRODUCTION

Table 1 summarizes major features of each of the overlay design procedures discussed above. The table shows the common features in overlay design procedures which use nondestructive testing, namely:

1. The season in which testing is performed for design purposes.
2. The location on the pavement where tests are made.
3. The frequency of testing along the pavement.
4. The need for taking cores and performing laboratory tests.
5. The non-destructive testing device(s) that are or may be used.
6. The measurements that are made with the NDT devices.
7. The other measurements that are made in addition to NDT.
8. The corrections that are made either to the NDT measurements or to the calculated pavement properties.
9. The properties of the pavement or layers that are calculated or inferred from the NDT measurements.
10. The methods that are used to distinguish between sections of pavement that require different thicknesses of overlay.
11. Empirical relations that are used to convert the NDT measurements to those that are used in design. These conversions may be:
    a. Correlations between the deflections measured with an NDT device and those produced by a design load,
    b. Correlations between layer material properties corresponding to the load level applied by the NDT device and the same material properties at design load level or
    c. Correlations between an NDT deflection and a design strain at a critical point in the pavement structure.

12. Empirical design relations that convert the measurement at design load into the number of load applications that the pavement can support.

Each of these twelve aspects of an overlay design procedure are discussed below.

Testing Season

The recommended testing season is normally the "critical period" for a pavement based on the time when deflections and stresses are the largest. There are some exceptions to this. The FHWA-RII (3, 4)method uses the annual average condition, the Utah (13) method uses the fall, and the Kentucky (9) method uses either a soaked CBR lab test or the minimum inplace subgrade modulus.

Test Location and Frequency

NDT tests are usually made on the pavement in the outer wheel path or in areas which show the major distress. Test sections around 1000 ft (305 m) long are selected. Tests are made every 50 to 500 ft (15 to 152 m). The closer spacing are normally used in areas with high severity distress or rapid changes in topography. The usual spacing is 100 to 200 ft (30 to 60 m). For reflection cracking purposes, deflections on the loaded and unloaded side of a crack or joint should be made, as well as deflections in the center of an intact section.

Required Coring and Lab Testing

The two overlay design methods which require lab testing of samples in the lab are the FHWA-ARE method (2) and the Kentucky method (9). The FHWA-ARE method requires tests of the asphaltic concrete, base course, subbase, and subgrade, the latter three in a triaxial apparatus at different levels of confining pressure. The resilient modulus of the asphaltic concrete is determined at the mean annual temperature. The Kentucky method determines a soaked CBR value for the subgrade sample and multiplies it by 1500 to get an approximate subgrade modulus.

Nondestructive Testing Devices Used

Each overlay design procedure has a principal NDT device and may have several alternates. The use of any alternate device usually requires a correlation between the deflections measured by each device. However, there are fundamental difficulties with this approach. As shown in References 3 and 9, the correlation between the deflections measured by two different devices changes with the thickness and modulus of each pavement layer and the modulus of the subgrade. Thus, there is really no unique multiplier which relates the deflections measured by one NDT device with that of another. The multipliers that have been found in field correlations must be regarded as applying only to those pavements on which the correlation was made.

Even when the primary device is used, care must the exercised to insure that the equipment has the configuration (loading plate size and shape, sensor locations, etc.) for which the overlay design procedure was developed. In addition, the equipment must be operated in the same manner (load level, frequency, etc.).

The primary devices used include the Dynaflect, Road Rater, Falling Weight Deflectometer, California Traveling Deflectometer and Benkelman Beam. The alternate devices include Dynaflect, Road Rater, Falling Weight Deflectometer, Benkelman Beam, and Dehlen Curvature meter. Further discussion of correlations is continued later.

As an alternative to correlating deflections from different NDT devices, the FHWA-RII method (3) provides for a separate analysis for each NDT device to determine the moduli of each layer in the pavement.

NDT Measurements

The NDT measurements which are made are either a single deflection, a deflection basin, or deflections on the loaded and unloaded side of a joint or crack.

Other Measurements

In addition to the NDT measurements, the following measurements are also made: date and time of test, air temperature, pavement surface temperature, thickness of asphalt layer, mean air temperature over previous 5-day period from a nearby weather station, and thickness of all layers from construction drawings. The air temperature should be measured every hour on bright, sunny days and as far apart as 3 or 4 hours on cloudy days with relatively stable air temperature. The temperature measurements are used in making temperature corrections using methods such as the one developed by Southgate (19).

Correction to NDT Measurements

Measured deflections are corrected to a standard condition which is used for design purposes. The most extensive set of corrections that are made to measured deflections are applied in Kentucky (9) where there are correction methods for load level, temperature, loading frequency, modulus, voids, and asphalt content of the asphaltic concrete surface layer. The normal corrections are for temperature and season.

Most areas of the country experience significant changes in surface temperature and subgrade moisture content. Therefore, a temperature increase tends to "soften" asphalt concrete while a temperature decrease tends to "stiffen" asphalt concrete. This in turn affects the deflection measured by NDT devices. A typical correction procedure requires measurement of the pavement surface temperature and determination of the mean five day air temperature to estimate the mean pavement temperature. This temperature is then used to determine a multiplier used to adjust maximum deflection from the determined mean to an equivalent maximum deflection at a standard temperature. All corrected deflections can then be compared (5, 19).

Some areas of the country experience significant seasonal variations in subgrade strength because of moisture changes and frost action. Figure 1 shows the type of variation which could be experienced. Of course subgrade materials also affect this variation, and Figure 2 demonstrates the effect of materials on season variation. Each agency must develop this relationship and adjust deflections to a standard adjusted deflection, measure deflections at a standard time, or determine that no significant variation exists. Seasonal adjustment factors should account for differences in subgrade materials as well. Thus, different adjustment factors may be required for different subgrade types.

California (8) makes no corrections except for temperatures below 50 degrees F (10 degrees C). Louisiana has a method (10) of correcting for moisture beneath the pavement using the spreadability-versus-maximum deflection chart. Some procedures, namely the FHWA-RII(3), University of Illinois (15), and the FHWA-ARE (2) methods, prefer to calculate the moduli of pavement layers directly from the NDT deflection measurements and then correct the moduli for temperature, stress level, and season. The FHWA-ARE method corrects only the subgrade modulus for stress level.

The FHWA-RII method assumes that all pavements are composed of three or four layers and corrects each layer modulus for temperature or stress level. The stress level corresponds to the level which is imposed by the design load. The Shell method (6) corrects the modulus of the surface course for temperature using a stiffness modulus chart that was developed for Falling Weight Deflectometer loading conditions.

Calculated or Inferred Pavement Properties

The pavement properties calculated or inferred from deflection measurements range from qualitative ratings of the pavement layers (Utah) (13) to layer moduli (FHWA-RII) (2). The pavement properties can be separated into five categories:

1. Qualitative ratings.
2. Representative deflections.
3. Representative basin properties.
4. Representative pavement structural properties.
5. Layer moduli.

The pavement section is normally represented by elastic layers (Figure 3 contains 4) of known thickness (except for the lowest layer which is assumed to have infinite depth) and characterized by Young's Moduli (E) and Poisson's ratios (m). When a load of known intensity is applied over a known area, deflections are created at some distance from the center of the loaded area. It is normally assumed that the load is distributed through the pavement system by a truncated zone (represented by the dashed line in Figure 3).

Based on this concept, the deflection d4 at a distance r4 from the center of load can only be due to the "elastic" compression of layer 4 since layers 1, 2 and 3 are outside the influence cone created by the load as shown in Figure 24. Likewise, the deflection, d3, at distance r3 is due to the compression of layers 3 and 4; the deflection at distance r2 is due to compression in layers 2, 3 and 4 and the deflection, d1, is due to compression in all layers.

This can be used, at least conceptually, to determine the influence of the various layers in the pavement structure. This general approach is used to "back-calculate" properties of pavement layers.

More subjective analyses consider just the curvature and maximum deflection to determine general behavior. This concept is illustrated in Figure 4 from the Utah overlay design procedure (13) which uses representative deflection and basin properties to arrive at qualitative descriptions of the condition of the surface, base, and subgrade. The Dynaflect Maximum Deflection (DMD), the Surface Curvature Index (SCI), and the Base Curvature Index (BCI) are all used to arrive at these ratings. The dividing lines between "good" and "poor" are 1.25 mils (DMD), 0.48 mils (SCI), and 0.11 mils (BCI). One mil is 0.001 in (0.0254 mm).

Representative deflections are usually those that are larger than a selected percentile between 50 and 97 percent as estimated using a normal distribution. These percentiles apply to deflections that are measured at a crack or joint or in between them.

Representative basin properties include the spreadability, the SCI, the BCI, and the "Area". These are normally used with maximum deflection to determine structural properties (representative or moduli) of pavement layers.

Representative structural properties of a pavement include the effective thickness of the pavement as in the Virginia (14) and Louisiana (10) methods, effective thickness of asphaltic concrete and base course as in the Kentucky method (9), and effective modulus in the Asphalt Institute method (5). Joint and crack load, shear, and deflection transfer efficiencies are calculated from deflections on the loaded and unloaded sides of cracks in the existing pavement.

Layer moduli that are calculated from deflection measurements usually include the subgrade modulus. However, in the FHWA-RII (3) all layer moduli are calculated for a 3 or 4 layer pavement. The Shell (6) procedure assumes a correlation between the subgrade and base course moduli and then determines the surface course modulus in an assumed three-layer pavement.

The University of Illinois procedure (15) assumes a modulus of the aggregate base course and determines the modulus of the asphaltic concrete and the "break-point" modulus of the subgrade, thus taking into account some of the stress-sensitivity in these layers.

Methods of Delineating Common Pavement Sections

There are two methods used to delineate common sections of pavement to receive a uniform overlay treatment: one differentiates sections based on deflections and visual condition and the other distinguishes sections based upon the required overlay thickness. In the first method, statistical tests are made using a mean and standard deviation of deflections of sections that are suspected of being different. In the second, used only by the FHWA-RII method (3), required overlay thicknesses are calculated for each deflection basin, and then statistical tests are made using the mean and standard deviations of the overlay thicknesses. In both methods, a change in overlay thickness is made only if there is a significant difference either in the design deflection or in the design overlay thickness between two sections that are believed to be different. The design deflection is the one which is larger than 50 to 97 percent of all other deflections in a section based on the reliability selected by the highway agency. The percentile for the design overlay thickness is thought to be between 67 and 75 percent, although there is not enough experience with the FHWA-RII method to say for certain. At present, the selection of the design percentile is left to the design engineer.

Empirical Relations Between NDT Measurements and Design Quantities

There are three types of correlations between NDT measurements and design quantities:

1. correlations between deflections produced by an NDT device and those produced by a design load,
2. Correlations between material properties at the load level produced by the NDT device and those same material properties at design load level, and
3. Correlations between an NDT deflection and a design strain at a critical point in the pavement

Correlations between deflections measured by different devices are most common in these overlay design procedures, and they are usually relations between the Benkelman Beam maximum deflection and that produced by the principal NDT device used in pavement evaluation. In Louisiana (10), Texas (12) and Utah (13), the correlation is with the Dynaflect and in general, the multiplier is usually found to be between 20 and 30. In Texas, the correlation was not between maximum deflections but between SCI values. In Pennsylvania (11), the correlation is between the Road Rater maximum deflection and the Benkelman Beam. In California (8), correlations are available between the Traveling Deflectometer and several other NDT devices including Dynaflect, Road Rater, and Dehlen Curvature Meter. Indiscriminate use of correlations can lead to significant error. Further discussion is presented later.

Correlations between material properties at different load levels are usually done with the aid of stress-strain curves of the material at different stress levels. This is the case with the subgrade in the

FHWA-ARE (2) and the University of Illinois (15) method and with the base, subbase, and subgrade in the FHWA-RII (3) method.

Correlations between an NDT deflection and a design AC strain is used in the University of Illinois method.

Empirical Design Life Relations

Every overlay design procedure has an empirical relation between the number of design load applications that a pavement can carry and a deflection, pavement thickness, or a calculated strain at a critical point in the pavement structure. In fact, overlay design procedures are fit into three categories based upon which value is used to specify the design life of the overlay:

1. deflection (based on deflections),
2. structural deficiency (based on thickness), or
3. mechanistic (based on a calculated strain).

Deflection overlay design procedures are used by the Asphalt Institute (5), the States of California (8), Louisiana (10), Pennsylvania (11), Texas (12), Utah (13), Virginia (14), and the new NCHRP-TTI design procedure (18). Texas is unique in relating pavement design life to the SCI rather than to maximum deflection.

Structural deficiency overlay design procedures are used by Kentucky (9) and by the Federal Aviation Administration (FAA) (17).

Mechanistic overlay design procedures are used in the FHWA-ARE (2), FHWA-RII (3), the Shell (6), and the University of Illinois (15) methods, all of which use a fatigue relation relating the strain at the bottom of the asphalt concrete layer to the number of design load applications. In addition, the FHWA-ARE method considers rutting and provides a stress-check procedure for reflection cracking.

In all cases, the design life relation is empirical in that it must be based upon field observations. The design strain is calculated for the design level of load and in all cases the stress sensitivity of the material in at least some of the pavement layers is taken into account in making this calculation.

Some of the commonly used NDT devices such as Dynaflect or Road Rater apply loads which are much smaller than the design loads. The moduli that are back calculated from the deflections measured by devices with small loadings do not correspond to the moduli used in calculating the design strain. This means, in practice, that the moduli from the lightly-loaded NDT devices must be adjusted to account for stress-sensitivity. This adjustment is not a constant but depends on the pavement section and materials in the pavements. Methods for doing this explicitly are included in the FHWA-ARE (2) procedure for the subgrade and in the FHWA-RII (3) procedure for all layers beneath the surface course. The Shell (6) and University of Illinois (15) methods use the Falling Weight Deflectometer which is capable of applying a design load level to an existing pavement.

Design Assumptions and Required Correlations For Overlay Design

The foregoing review of overlay design procedures shows that all design methods which use NDT are based upon at least one design assumption and one related NDT empirical correlation. The design assumptions which have been used or might be used are listed below. The number of design loads (18,000 lb ESAL) (80 kN) in the useful life of an overlay is related to one or more of the following:

1. The deflection it experiences under that design load.
2. The amount of bending (SCI) it experiences under the design load.
3. The effective thickness of the pavement above the subgrade.
4. The tensile strain at the bottom of the asphaltic concrete layer under a design load.
5. The compressive strain either in the subgrade or in the asphaltic concrete overlay material under a design load.
6. The distressed condition of the underlying pavement and to the thickness of the overlay.
7. The differential deflection across cracks or joints in the underlying pavement due to the application of the design load, and to the thickness of the overlay.

Obviously, still other design assumptions could be made. In every case, however, the relation described in the design assumption must be determined empirically and must be based upon field observations.

The use of a nondestructive testing device in an overlay design procedure requires that a related correlation must be developed between the results of the NDT measurement and the design quantity which is assumed to control the useful life of the pavement. Typical required correlations are as follows:

1. Deflections under the design load correlated with deflections under the NDT device.
2. Bending (SCI) under the design load correlated with the bending (SCI) under the NDT device.

3. Strain under the design load correlated with the deflection or strain under the NDT device.
4. Layer modulus under the design load correlated with the layer modulus under the NDT device.

It should be noted that the first and second correlations would not be needed if if the NDT device produced deflections and bending equivalent to that produced by design loads. The third and fourth correlations are used with mechanistic design procedures. In principle, any NDT device can be used with any design procedure provided that the "required correlation" can be found. As a caution, it is noted that the "design assumption" must also be shown by field observations to be valid for the pavement where it is to be applied. In general, those NDT devices which simulate design loads and produce equivalent deflections will be the most simple to use resulting in less error due to correlations.

Evaluation of Current Overlay Design Procedures For Compatibility With Available NDT Devices

Each of the above "required correlations" relate NDT measurements to the design quantity that appears in the "design assumption" of an overlay design procedure. For the equipment to be compatible with the design procedure, this correlation must be possible. The NDT devices were separated into four categories: static deflection, automated beam deflection, steady state dynamic deflection, and impulse deflection.

The static deflection devices include the Plate Bearing Test, the Curvature meter, the Benkelman Beam, and the Deflection Beam. For both of the beams, it is possible to develop, either by observation or analysis, all four of the "required correlations", i.e., deflection, curvature, strain, or layer modulus. For the curvature meter, the only "required correlation" it can develop is for curvature. For the Plate Bearing Test, it is possible to develop, either by observation or analysis, all of the "required correlations" except for curvature.

The automated beam deflection devices include the La Croix Deflectograph and the California Traveling Deflectometer. It would be simpler to develop a "required correlation" for deflection or strain with these devices than for curvature or layer modulus. Theoretically, the "required correlation" for layer modulus could be developed using some form of mechanistic analysis since the La Croix can be used to measure basin responses.

The steady state dynamic deflection devices include the Dynaflect and the Road Rater Models 400B, 2000 and 2008. In each of these, deflections are measured at a number of points on the pavement surface which makes it possible to determine deflections and curvatures directly and to calculate strains and layer moduli. Because of this, the "required correlations" can be developed with each of these devices in principle.

The impulse deflection devices include the Dynatest, KUAB, and Phoenix Falling Weight Deflectometers, and the wave propagation devices currently being developed at the University of Texas and at the University of New Mexico for the U.S. Air Force. Because all falling weight deflectometers measure deflections at several points on the pavement surface, it is possible in principal to develop all four "required correlations" with them. In addition, these devices produce impulse loads equal to design loads. The deflections produced by these devices have been shown to closely simulate moving wheel load deflections. This allows in principal the direct use of the deflection, bending strain and modulus data without correlations.

The wave propagation methods both produce moduli of the pavement layers which correspond to a light load. Consequently, in order to use the wave propagation techniques it is necessary to develop the "required correlation" between layer moduli at different load levels. This is the only "required correlation" that can be used with the wave propagation methods.

Correlations Between NDT Devices

Since correlation between NDT devices is the most common correlation used in overlay design procedures, additional discussion is presented.

In general, a different correlation should be developed for each major pavement type and for different pavement thicknesses within particular types of pavement because the correlation is not unique, as was shown very clearly in Reference 3. Correlations will also change with loading frequency, as is illustrated in Kentucky's method, in which there is a correction to a standard loading frequency of 25 Hz.

Since several of the overlay design procedures presently available were developed based on AASHO Road Test Data and other deflection data from the Benkelman Beam, deflection measurements from other devices have often been converted to equivalent Benkelman Beam deflections by several agencies. A few for the Dynaflect are summarized below to illustrate the variability which can be expected:

Arizona:

BBD = 22.5 (DMD)

where:
BBD = Benkelman Beam Deflection
DMD = Dynaflect Maximum Deflection

No data on the basis of the correlation was given. Arizona also uses the California overlay design method with their correlation between Dynaflect and travelling Deflectometer (20).

Virginia:

No. of Points Correlated	Tests	r	Se (.001")	Regression Equation
All points flexible	107	.852	9.8	BB=30.5 D - 12.3
Stabilized Base	72	.918	5.4	BB=24.0 D - 8.0
Unstabilized Base	35	.877	9.6	BB=32.8 D - 8.6

where:
BB = Benkelman Beam Deflection (in x 10-3)
D = Dynaflect Deflection (in x 10-3)

Benkelman Beam deflections are taken approximately as recommended in AASHTO T256-77; however, the tip is placed only 2 ft (.6 m) forward of the wheel at the start of the test versus 4 to 4.5 ft (1.2 to 1.4 m) recommended in T256-77. Also, the final position of the truck differs from that recommended by T256-77. The tests were taken from 7 flexible projects. Four of the projects had stabilized bases (21).

Asphalt Institute:

BB = 22.30 D -2.73

where:
BB = Benkelman Beam Rebound Deflection (in x 10-3)
D = Dynaflect Center Deflection (in x 10-3)

Benkelman Beam deflections are rebound deflections based on the Canadian Good Roads Association (CGRA) procedure. No information on number of test points, test locations, pavement types, etc. is provided for the regression equation, however, they reflect a composite analysis (5).

Louisiana:

$$BB = 20.63\ D$$

where:

BB = Benkelman Beam Rebound Deflection (in. x 10-3)
D = Dynaflect Deflection (in. x 10-3)

This equation is based on 54 comparisons on 20 pavement sections of flexible pavement. The correlation coefficient was 0.85 (10, 22, 23).

Correlations between most other devices and the Benkelman Beam have been developed by various agencies. Correlations have been developed between different dynamic deflection devices, between dynamic deflection devices and impulse devices, etc. An agency which is developing such a correlation should use those developed by another agency as a guide only. The actual correlation must be developed for the agency's own test procedures, pavement sections, soil types and environmental conditions to be valid. Even then, all of the problems discussed in Reference 3 may be encountered. As discussed previously, there is no unique multiplier which will accurately relate the deflection measured by one NDT device to the deflection measured by another. Changes in pavement layer thicknesses and moduli will affect any such multiplier (3, 13).

Table 2 was prepared to show typical Benkelman Beam to Dynaflect correlations. It shows a large range of values for equivalent Benkelman Beam deflections calculated from the same Dynaflect reading. This is included primarily as a caution to highway engineers that a correlation developed by one agency may not be directly transferable.

It should be noted that NDT equipment which can reproduce design loads and simulate moving wheel load deflections eliminates the need for many of the correlations. They also eliminate the error associated with correlations.

Interchangeability of Data

Many times agencies vary in their testing programs which makes use of another agency's data difficult even when they use the same type of equipment. For instance, agencies using the Road Rater may vary considerably in the load, frequency, loading plate configuration and sensor location any which will have a significant impact on the deflection data. Some agencies using the Benkelman Beam use the WASHO method (24) while others use the rebound method (5), making the results difficult compare the results. Even the weights used for Benkelman Beam measurements vary. Early California measurements used 7,500 lb. (33 kN) wheel load and later a 9,000 lb. (40 kN) wheel load (7, 8). The British use a 7,000 lb. (31 kN) wheel load (25), and Florida uses a 10,000 lb (44 kN) axle load (26).

This indicates the problems that can develop in trying to use data developed by another agency. The source, testing procedure, and equipment configuration used in developing the data must be fully understood before data collected by another agency can be used. Failure to consider these can lead to significant error if data, or correlations based on that data, are used.

CONCLUSIONS

The following conclusions were made based on the data presented in the report:

1. Several overlay design procedures for flexible pavements which use deflections have been developed. The mechanistic based procedures can be used more directly by agencies other than the developing agency. Some field verification is still necessary with mechanistic procedures.
2. In developing, or selecting, a deflection based overlay design procedure, the following items should be considered:
   a. Seasonal influences on the deflections.
   b. Location of test points on the pavement surface.
   c. Frequency of testing.
   d. Need for cores and laboratory testing.
   e. Type of NDT measurements (i.e. maximum deflection, basin characterization, etc.).
   f. Additional field measurements that are required.
   g. Corrections to NDT measurements for temperature, etc.
   h. Pavement properties calculated or inferred from the NDT measurements.
   i. Method used to distinguish between different design sections.
   j. Relationships which are used to convert NDT measurements to design parameters.
   k. Relationships which relate the design parameters to the useful life of the pavement.

l. The nondestructive testing devices which are available for use.

m. Consideration of existing deterioration of the pavement.

3. If a NDT device produces a load less than the design load one of three general methods must be used to convert the measured deflections into usable parameters:

   a. Correlate the NDT deflection measurements from the light load device with those produced by the design load.

   b. Correlate the material properties calculated from the NDT device with those same properties which would be developed for the design load.

   c. Correlate the light load deflection measurements with some measure of performance directly.

   All of these methods may produce questionable results because of the stress sensitivity of the pavement/subgrade.

4. There are significant advantages for using a NDT load that equals that of a heavily loaded truck wheel load (e.g. 9000 lb). The response of the pavement to this heavy load can be accurately measured and directly used for structural evaluation and overlay design without questionable correlations or stress sensitivity assumptions.

5. Available correlations are valid only for the typical pavement sections, materials, and environmental conditions affecting the pavement sections for which the correlations were developed.

RECOMMENDATIONS

1. Correlations of deflection measurements between devices should be used only with a complete understanding of the conditions for which they are applicable and an understanding of the magnitude of error involved.
2. NDT response is load dependent. Analytical procedures to accurately characterize and model material properties which are stress dependent should be improved and refined. As additional layers of overlays are added to pavements, this becomes more critical.
3. Any overlay design procedure developed or adopted by an agency must be carefully field calibrated for local conditions and materials. This will require the use of actual, in service pavement sections.
4. Computerized overlay design procedures should be made available to the field engineer who evaluates pavements and designs overlays. Computerized methods should be developed for use with microcomputers (256K or less).

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Table 1. Major features of selected overlay design procedures.

Overlay Design Procedure	NDT Device (p) primary (a) alternative	Type of Overlay Design Method	NDT Measurements	Corrections		Calculated or Inferred Pavement Properties	Section Delineation Criteria	Empirical Relations	
				NDT Measurements	Pavement Properties			Required Correlation	Design Assumption
FHWA-ARE (2)	Dynaflect	M	Deflection Basin Design Deflection Based on Selected Reliability			Subgrade modulus	Statistical * difference max deflection Severity alligator crack	Layer moduli	Fatigue, rutting from AASHO Road Test
FHWA-RII (3,4)	(p) Dynaflect (a) Road Rater (a) FWD (trailer) (a) FWD (van)	M	Deflection Basin (4 deflections)		Surface Course Modulus for Temperature Stress Level of Base, Subbase, & Subgrade Moduli	Moduli of layers in a 3 or 4 layer pavement	Statistical difference required overlay thickness	Layer moduli	Fatigue from AASHO Road Test
Asphalt Institute (5)	Benkelman Beam	D	Deflection (97 percentile)	Temperature Season		"Effective modulus" of pavement	Statistical difference max deflection	Deflection	Design deflection vs 18 k ESAL/day
Shell Oil (6)	Falling Weight Deflectometer	M	Deflection Basin		Surface Course Modulus for Temperature	Layer Elastic Modulus	Statistical difference max deflection	Layer moduli Correlation between subgrade and base modulus	Fatigue: strain vs no. of design loads
California (7,8)	(p) Traveling Dfl (a) Benkelman B (a) Dynaflect (a) Road Rater (a) Dehlen Curvature Meter (a) FWD	D	Deflection (80 percentile)	Temperature below 50°F			Difference > 0.01" in 80 percent deflection	Deflection	Tolerable deflect vs design traffic % deflect reduc. vs overlay thick
Kentucky (9)	Dynaflect	SD	Deflection Basin Max Deflection (50-90 percentile)	Load Level Temperature Load Frequency AC Modulus air voids asphalt content		Subgrade modulus Effective AC thickness Effective base course thickness	Significant difference in 90 percen. deflec., subgrade mod., or AC thick	Road Rater deflection vs subgrade modulus	Total pvt thick vs 18k ESAL for var. CBR's %AC in pvt structure
Louisiana (10)	Road Rater	D	Max Deflection (95 percentile)	Temperature Moisture		Subgrade stiffness Spreadability Effective pavement thickness	Statistical difference max deflection	Deflection Dynaflect vs Benkelman Beam	Tolerable deflect vs 18k ESAL % deflect reduc. vs overlay thick
Pennsylvania (11)	(p) Road Rater (a) Dynaflect	D	Deflection Basin (90 percentile)	Temperature Season				Temp. adjust vs surf. temp. Deflection Road Rater vs Benkelman Beam	Road Rater deflect vs 18k ESAL design life
Texas (12)	Dynaflect	D	Deflection Basin			Surface Curvature Index (SCI)	Statistical difference max deflection	Deflection Dynaflect vs Benkelman Beam	Loss of serviceability index related to SCI and No. of 18k ESAL
Utah (13)	Dynaflect	D	Deflection Basin Max Deflection (80 percentile)	Temperature		SCI, BCI Qualitative condition of surface, base, & subgrade	Statistical difference max deflection	Deflection Dynaflect vs Benkelman Beam	Max. deflection vs No. of 18k ESAL
Virginia (14)	Dynaflect	D	Deflection Basin Max Deflection			Spreadability Subgrade modulus Effective pavement thickness	Statistical difference max deflection	Deflection Dynaflect vs Benkelman Beam	Max. deflection vs No. of 18k ESAL
University of Ilinois (15,16)	Falling Weight Deflectometer	M	Deflection Max Deflection (84-97 percentile)		Temperature Stess Level	Basin Area AC Modulus Break point modulus of subgrade	COV of max deflection > 20 percent	Strain vs Deflection Road Rater vs Falling Weight Deflectometer	Fatigue: Strain vs No. of 18k ESAL
FAA/WES (17) (Lytton Critique)	Falling Weight Deflectometer	SD	Deflections at joints, cracks, & centers			Joint or crack load, shear, & moment transfer efficiency		Equivalent pavement section	Bonding condition vs exponent
NCHRP/TTI (18)	Falling Weight Deflectometer	D	Deflections at joints, cracks, & centers			Joint or crack load, shear, & moment transfer efficiency		Deflection	Joint or crack deflections vs No. of 18k ESAL

D Deflection
SD Structure Deficiency
M Mechanistic

* Statistically Different Maximum Deflection

Table 1. Major features of selected overlay design procedures (continued).

Overlay Design Procedure	NDT Device (p) primary (a) alternative	Test Season	Test Location	Test Frequency	Cores Required	Laboratory Testing
FHWA-ARE	Dynaflect	"Worst" season/ high deflect			ACZ Base Subbase Subgrade	Resilient modulus Triaxial Triaxial Triaxial
FHWA-RII	(p) Dynaflect (a) Road Rater (a) FWD (trailer) (a) FWD (van)	Annual average condition	Outer wheel path	50'-150'		
Asphalt Institute	Benkelman Beam	"Critical" period				
Shell Oil	Falling Weight Deflectometer					
California	(p) Traveling Dfl (a) Benkelman B (a) Dynaflect (a) Road Rater (a) Dehlen Curvature Meter (a) FWD	Spring to early summer	Outer wheel path 1000' long sections	50'		
Kentucky	Dynaflect	Soaked subgrade CBR or time of weakest subgrade			Subgrade	Soaked CBR test
Louisiana	Road Rater		Wheel path with most distress 0.2 mi long section	0.05 mile (264')		
Pennsylvania	(p) Road Rater (a) Dynaflect	Spring	Outer wheel path, areas of greater distress 1000' sections	100'		
Texas	Dynaflect					
Utah	Dynaflect	Fall	Closer spacing around heavy cracking			
Virginia	Dynaflect			500' or less		
University of Illinois	Falling Weight Deflectometer	Spring	Outer wheel path	100'-200'		
FAA/WES (Lytton Critique)	Falling Weight Deflectometer					
NCHRP/TTI	Falling Weight Deflectometer					

Table 2. Benkelman Beam readings (x10^{-3} inches) determined from correlations with Dynaflect. (1 in = 25.4mm)

Dynaflect Reading (0.001 inches)	Arizona	Asphalt Institute	Virginia (all flexible)	Louisiana
0.5	11.2	8.4	3.0	10.3
1.0	22.5	19.6	18.2	20.6
1.5	33.8	30.7	33.4	30.9
2.0	45.0	41.9	48.7	41.3
2.5	56.2	53.0	64.0	51.6
3.0	67.5	64.2	79.2	61.9

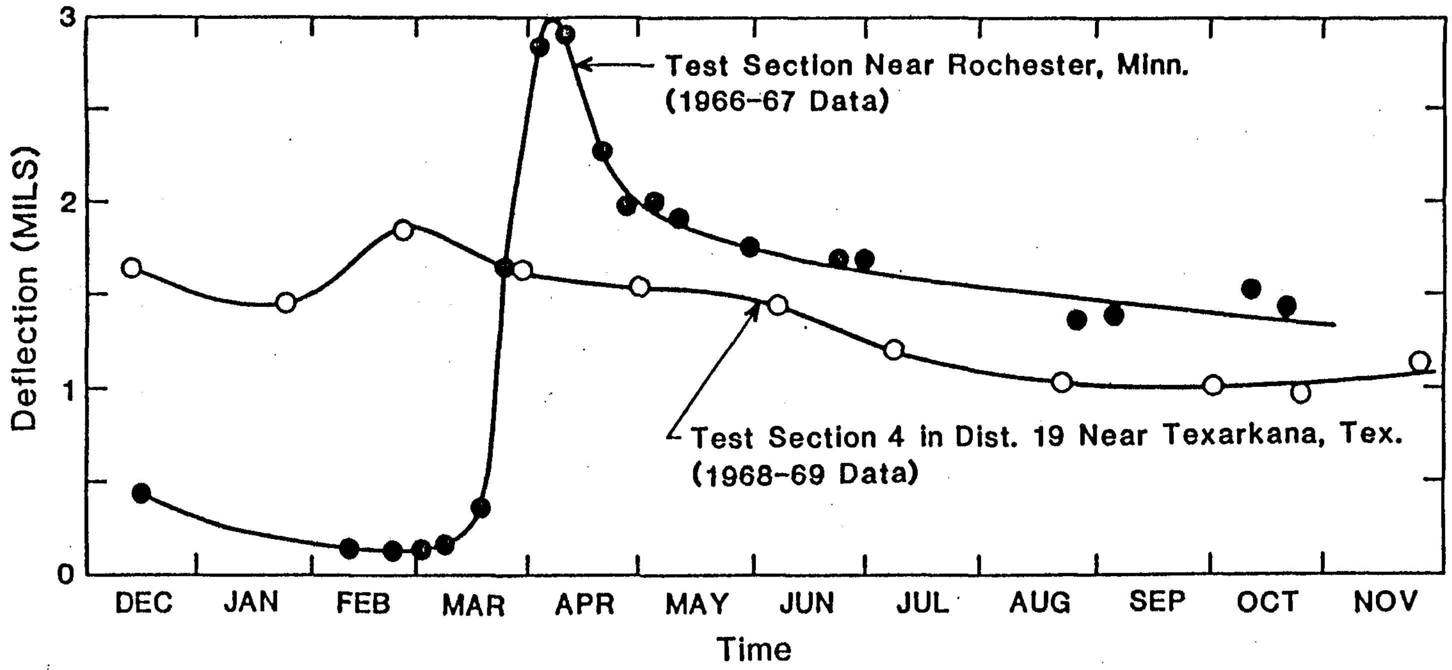

Figure 1. Effects of seasonal influence on deflections in different climatic areas, from Reference 5.

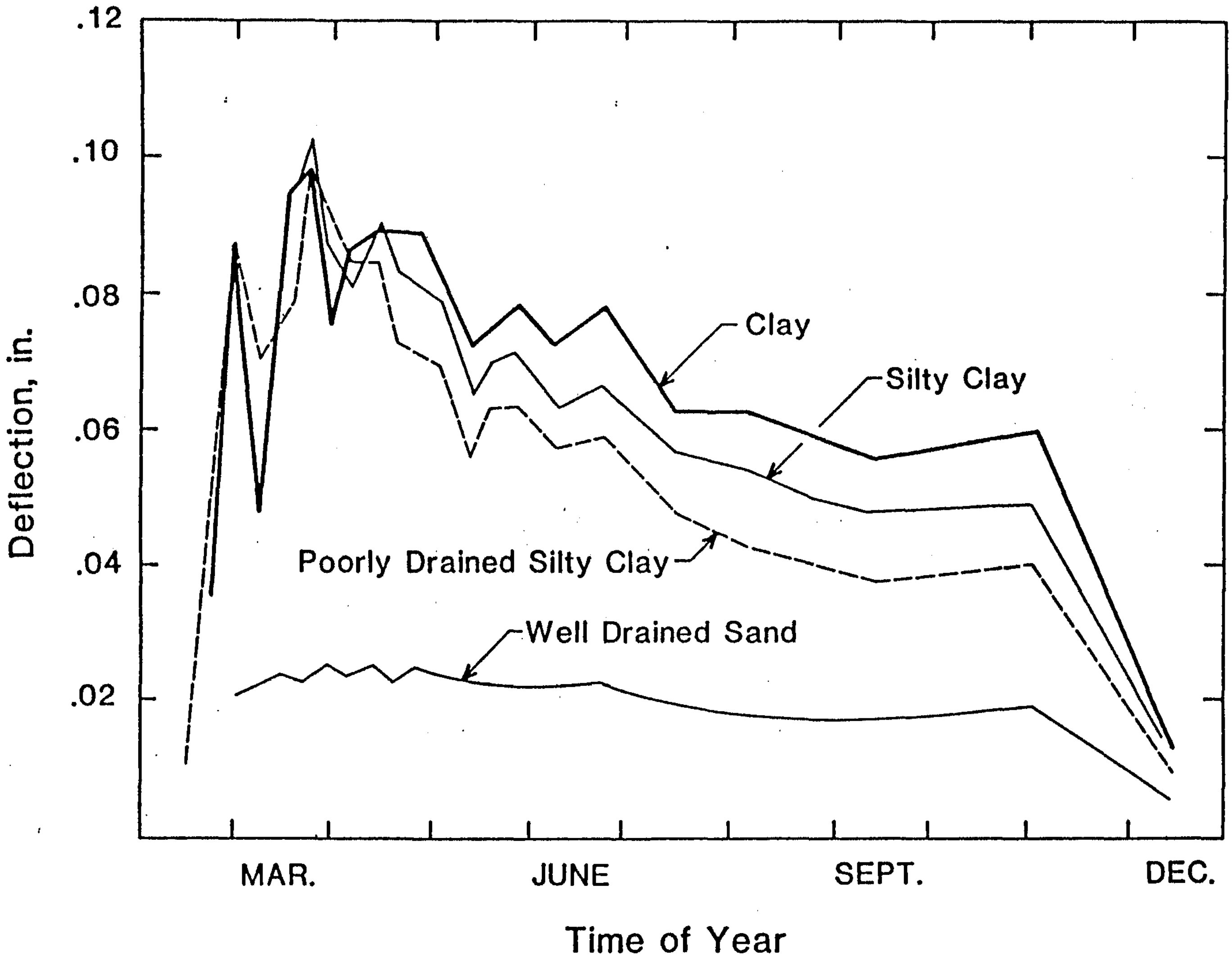

Figure 2. Effects of subgrade materials on seasonal influence on deflections. (1 in = 25.4mm)

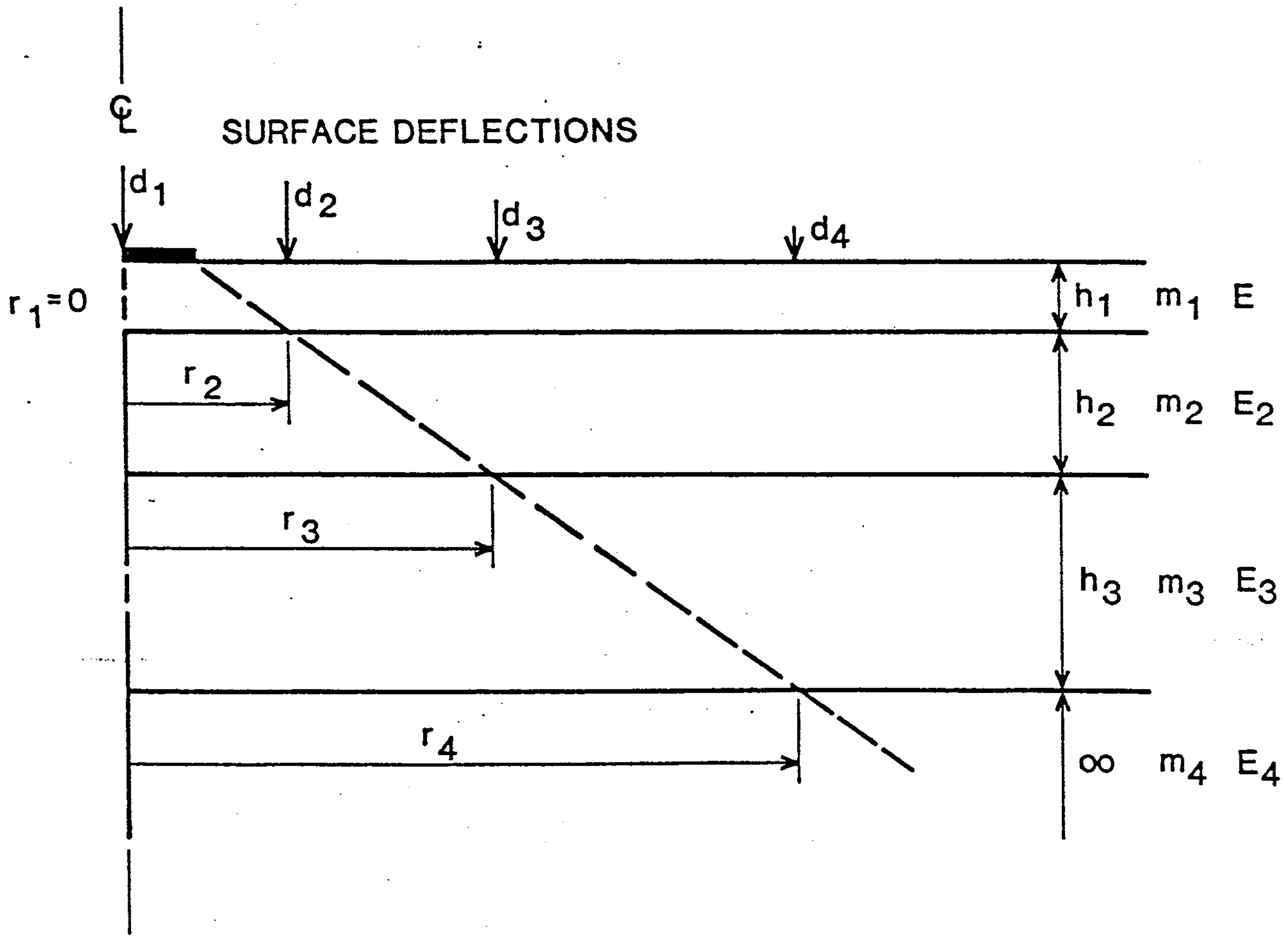

Figure 3. Four layer elastic representation of a pavement system.

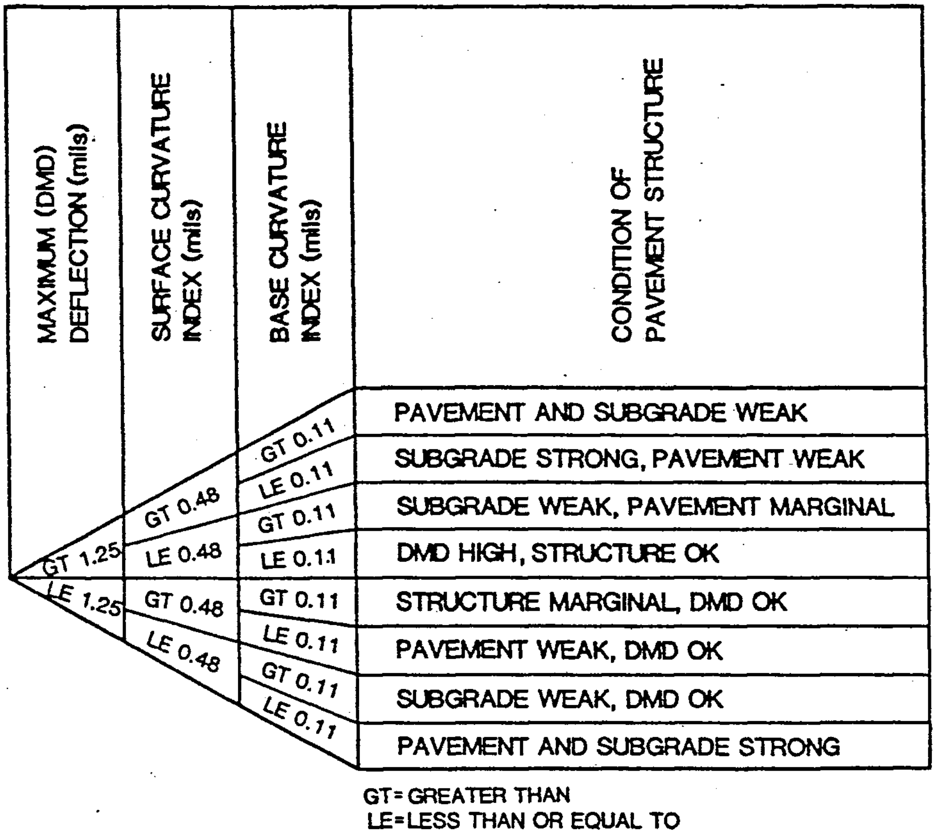

Figure 4. Use of deflection basin parameters to analyze pavement structural layers from Reference 13. (i mil = 25.4μm)