SUMMARY

Preliminary AC overlay design concepts for flexible pavements based on NDT data have been presented in this paper. The NDT data must be related to a moving 9-kip wheel load response. The FWD device is well suited for this purpose. In this paper, conventional pavements (surface treatment + granular base and AC surface + granular base) and full-depth AC pavements (AC surface + AC base) are considered. Procedures for field evaluation and NDT testing, NDT data interpretation, and overlay thickness determination are proposed.

As implementation activities proceed, modifications or refinements may be needed. Special attention should be directed to developing a procedure that is readily understood and easily used but maintains the theoretical correctness of the proposed procedure.

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The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Illinois DOT or the FHWA. This paper does not constitute a standard, specification, or regulation.

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Overlay Design of Flexible Pavements: OAF Program

KAMRAN MAJIDZADEH, GEORGE J. ILVES AND RICHARD W. MAY

A fully computerized rational method for the design of flexible overlays of flexible pavements is presented. The overlay thickness is determined based on a fatigue distress function developed from analyzing AASHO Road Test data. It relates horizontal tensile strain in the asphalt layer to the number of equivalent 18-kip (80-kN) axle loads to failure. A rutting criterion is not included because (a) rutting in unbound layers has generally stabilized by the time an overlay is contemplated, (b) rutting in the asphalt layer can be controlled by proper mix design, (c) the addition of an overlay decreases the stresses in the unbound layers, and (d) fatigue requirements generally dictate the overlay thicknesses. The existing pavement is evaluated by using nondestructive dynamic deflection measurements and a visual survey that includes general observations of drainage, the existence of rutting, and the presence and type of cracking. The deflection data are analyzed by using linear elastic theory in which the existing pavement is represented by a four-layer model consisting of a pavement layer, base and subbase layers, and a subgrade layer. The in situ layer stiffnesses are determined by matching measured deflections with those computed from layer theory. The design procedure recognizes that asphalt modulus is temperature-dependent. The in situ asphalt modulus is modified for temperature effects, and this adjusted modulus is used in design computation. The base and subgrade materials are corrected for stress effects when the state of stress is changed as a result of adding an overlay. The procedure also incorporates an environmental factor.

An existing pavement may require an overlay for various reasons, such as fatigue cracking, low skid resistance, rutting, and surface deterioration in the form of spalling or raveling. The decision whether or not to overlay a given pavement is usually based on criteria that are almost universally recognized. However, there is no universally recognized or applied overlay design method that yields an adequate but not excessively thick overlay that will perform satisfactorily for some time.

In this paper an overlay design methodology is presented based on nondestructive testing (NDT) deflection analysis, with consideration of multilayer elastic systems and pavement evaluation methodology.

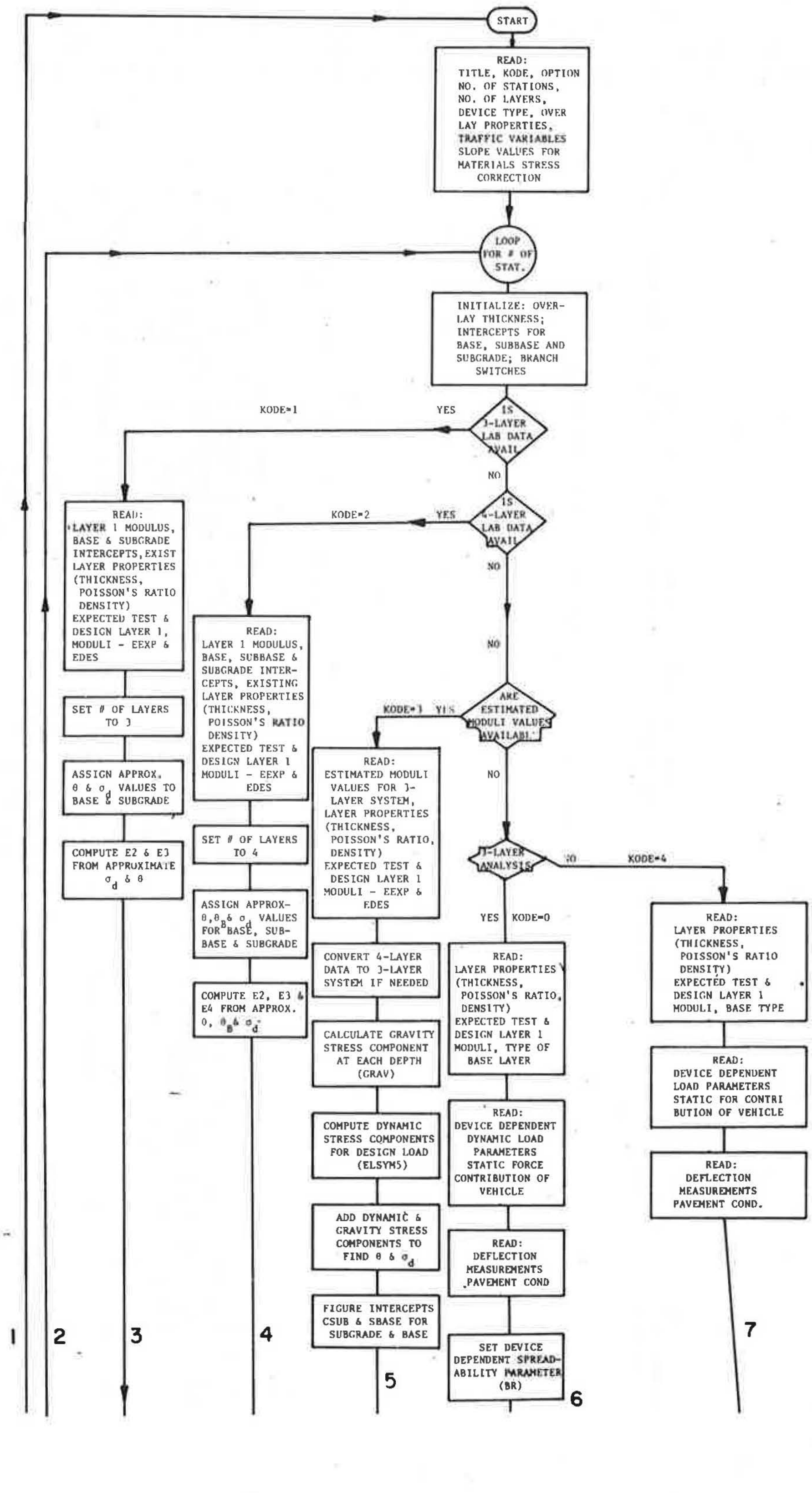
DESIGN CRITERIA

Scope of Procedures

The design procedure described in this paper is not intended to establish maintenance and repair needs and priorities; rather, it attempts to determine the required overlay thickness after the decision to overlay is made. An overlay thickness is selected based on a fatigue cracking model developed from AASHO Road Test data and tempered by experience and other studies. The procedure does not consider rutting as a distress mechanism, primarily because rutting of overlayed pavements in the United States is most often associated with unstable paving mixes; nor is it intended to consider localized distress modes caused by expansive soils or severe environmental stresses.

Because the fatigue model is based primarily on AASHO Road Test data (1), this procedure infers that the overlay materials and construction specifications will not significantly differ from those now in use. However, overlays that use reinforcing

Figure 1. Simplified flowchart of OAF.

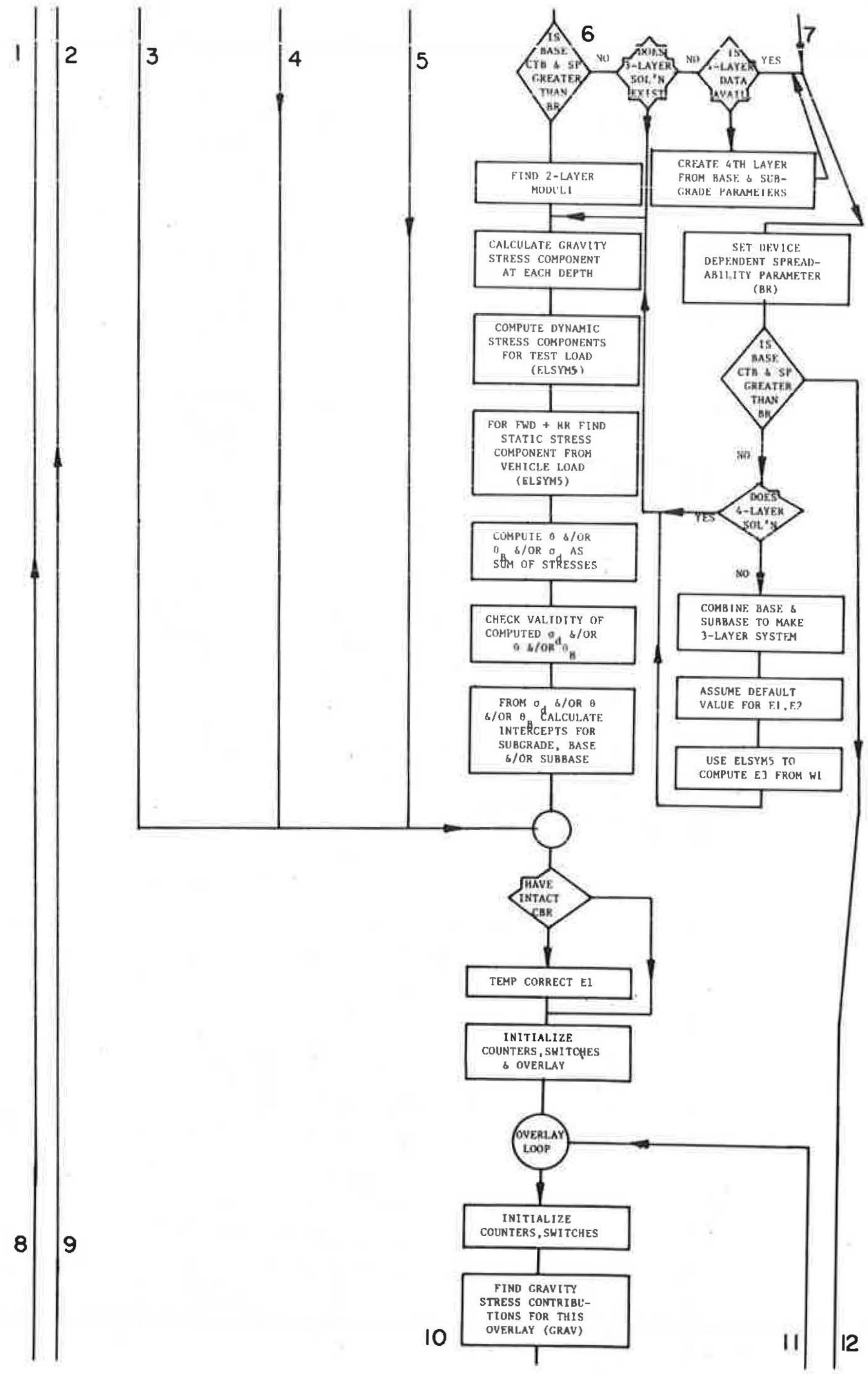


fabric and improved paving mixtures such as sulfur- and latex-modified asphaltic materials can be accommodated by appropriate modification of the distress function.

The primary design procedure is based on determination of in situ pavement layer properties from NDT deflection measurements on existing pavements. The procedure determines the overlay thickness requirements for each test location so that areas that require significantly thicker overlays readily stand out. This enables the designer to consider partial or total reconstruction, recycling, or other remedial measures such as drainage improvement before overlay. The designer can vary the overlay thickness along the highways as required by field conditions and also select an appropriate reliability level for design.

Figure 1 presents a simplified flowchart that shows the steps and decisions used in the program. Along with the basic procedure, several other options are offered, including the use of laboratory-determined layer properties in a four-layered pavement system and the use of estimated layer properties as default values. The use of data obtained by laboratory testing is for purposes of diagnosis and verification for those areas where laboratory test data for layer moduli are (or become) available. The option of using default values is included primarily for design purposes and may be used for the

Figure 1. Continued.



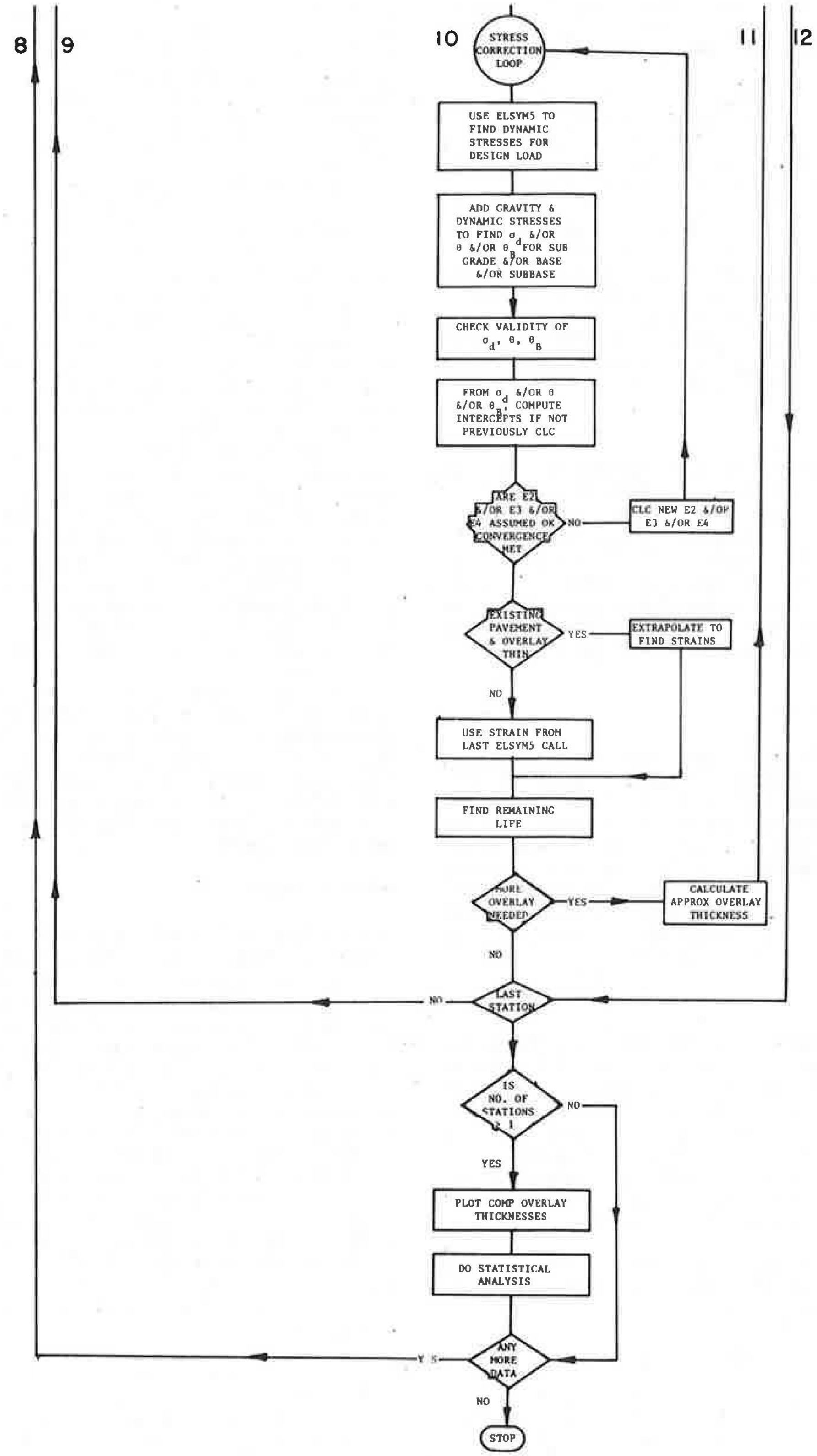
evaluation of the relative effectiveness of various base or pavement materials.

The computational procedures are completely computerized, and the overlay thicknesses are printed out in a graphic format as a function of locations along the roadway. On the basis of this test plot, the designer can divide the overlay project into various sections with similar overlay requirements. A seperate small computer program is used to determine the statistical significance of this division, if required by the engineer.

Existing Pavement Evaluation

It is recommended that estimation of in situ conditions be based on rational procedures, such as the

Figure 1. Continued.



procedures developed by using measured pavement surface deflections and the shape of the deflection basin to evaluate the in situ layer moduli. The proposed evaluation procedure for the standard FHWA method, OAF, is based on measured pavement deflections of a four-layer system representing the pavement structure.

The four-layer model is based on elastic layer theory and assumes that the pavement is made up of an asphalt layer, a base layer and subbase, and a semi-infinite subgrade layer. The layer stiffnesses are determined from measured deflections by iterative means until the computed deflections match the measured deflections.

In this standard design procedure, because the entire overlay design methodology is computerized, all necessary computations, such as determination of the remaining pavement life and the amount of overlay required, can be carried out in one program.

The design procedure is based on the effective-modulus concept rather than the effective-thickness approach because the effective-thickness concept requires a priori knowledge of the asphalt and base layer moduli and the computation methods required to solve for effective thicknesses are much more complex. Of course, the effective-modulus approach requires that layer thicknesses be known, but these are usually available from construction records.

STRESS CORRECTION

Commercially available pavement deflection testers generally apply loads that are smaller than the load resulting from an 18-kip (80-kN) axle. Because most subgrade materials and granular bases have moduli that depend on applied stresses, it is necessary to adjust the moduli determined from deflection measurements to design conditions--i.e., apply a stress correction. The OAF design model includes a stress correction for the subgrade and the base and subbase layers.

PAVEMENT TESTING PERIOD

Although it is desirable that pavement evaluations be carried out at a most critical period of the year, it is believed that such a field evaluation might lead to an overly conservative design. It is recommended that field measurements be conducted at a time when statewide field evaluation is convenient and also when base and subgrade values have stabilized and represent, as an approximation, average annual conditions. The resultant measurements are then adjusted to a critical condition.

Environment

The effect of environment is reflected in the pavement response under various environmental conditions. To adjust the pavement measurements to those of the most critical period, regional factors have been developed for various climatic conditions. The regional factor is a multiplier to the traffic intensity that replaces the damage at a weakened environmental condition by an equivalent increase in the traffic-induced damage at a reference environmental condition.

The pavement temperature is adjusted by means of a temperature adjustment factor and measurements of mean air temperature.

Analysis of Deflection Data

Most deflection-based overlay design methods use statistical techniques to combine deflections measured at different locations within an overlay project and thus arrive at a design deflection that represents the overlay project. These methods assume that a relationship exists between maximum deflection and overlay thickness--i.e., that deflection alone governs the amount of overlay needed. The proposed standard design procedure, however, evaluates the conditions of each layer in the pavement and determines the overlay requirements based on these values.

An overlay may be required for reasons other than large increases in user traffic. A pavement may, and generally does, require an overlay either because the asphalt, base, or subgrade layer is weak or because all three are weak at any one location. The amount of overlay required to correct each of these deficiencies is different, and each condition has a different effect on the shape of the deflection basin.

The subgrade support value has a great effect on the magnitude of measured deflections but a much smaller effect on the shape of the deflection basin. On the other hand, the stiffness of the asphalt layer has a greater effect on the shape of the deflection basin than on the magnitude of deflections. It is therefore apparent that combining deflection measurements from different locations within the overlay project to form representative deflections and using these values in the analysis model may result in an evaluation that is not representative of any part of the project.

If deflection data at each test location are analyzed separately, the in situ stiffnesses at these locations are determined along with the required overlay thickness. This allows the user to divide the overlay project into sections that have similar overlay needs and to vary the overlay thickness accordingly. Because the amount of overlay required depends not only on the maximum deflection but also on the shape of the deflection basin, such delineation is almost impossible from deflection data alone.

Areas that require thick overlays readily stand out; alternative rehabilitation strategies such as reconstruction or recycling may become economically desirable. Furthermore, because in situ layer stiffnesses are available at each test location, areas with reduced base and subgrade stiffnesses may benefit from improved drainage, which reduces the amount of overlay needed.

ANALYSIS MODEL

The overlay design scheme presented in this paper is based on elastic layer theory, which characterizes an existing pavement as a semi-infinite layered half-space consisting of a number of homogeneous and isotropic layers between which there is full friction. The layer properties are represented by modulus of elasticity and Poisson's ratio. A dual-tire truck wheel is represented by two uniformly loaded circular areas, the center-to-center distance of which is the same as that of a typical truck wheel.

The steps used in the overlay design procedure are shown in the flowchart in Figure 1. This flowchart has been simplified and condensed for the convenience of the user. The actual flow of information is quite complex, and it would require many pages to describe all of the branches and switchbacks.

The following major steps are used in the analysis program:

1. Layer properties are determined from NDT deflections.
2. Layer stiffnesses are adjusted for temperature- and stress-dependence effect.

3. The remaining life (RLIFE) is computed.
4. Overlay thickness (HOV) is incremented, layer stiffnesses are readjusted for changed states, and the remaining life is recomputed.

Step 4 is used and repeated until the remaining life equals the design life.

The four steps are repeated for each test location. After the last overlay calculation, the required thicknesses are plotted as a function of test location and a statistical analysis is performed. This statistical analysis computes the average overlay thickness along with the 67th, 77th, 87th, and 97th percentile values. The program does not attempt to group the overlay project into sections that have similar overlay needs; this is left for the design engineer.

In step 1, the following input data are required:

1. Dynaflect or falling weight deflectometer (FWD) measurements;
2. Base type (i.e., granular or cement-treated);
3. Layer thickness;
4. Poisson's ratios of all layers;
5. Modulus of pavement asphalt at test temperature and design temperature (EEXP and EDES);
6. Modulus of overlay asphalt (EOV);
7. Whether class 2 or class 3 cracking exists (1); and
8. Slopes of base, subbase, and subgrade modulus-stress relationships (B1, B2, B3).

As can be seen from the flowchart in Figure 1, pavements with cement-treated bases are analyzed somewhat differently from pavements with granular bases. For pavements with granular bases, subroutine DYNAFL is used to compute the in situ layer stiffnesses from measured deflections and the shape of the deflection basin, as defined by

$$SP = 100 * \left(\sum_{i=1}^{5} W_i\right)/5W_1 \quad (1)$$

where W_i are the measured deflections and W_1 is the maximum deflection.

Two strategies are used to determine layer stiffnesses: (a) matching measured and computed W1, W2, and SP and (b) matching measured and computed W1, W3, and SP. After the layer stiffnesses have been determined, the ELSYM5 program is used to compute the deviatoric stress (σ_d) and the sum of principal stresses (θ) for the equivalent tester load, and the constants A1 and A2 are determined from

$$A1 = E2\ \theta^{-B1} \quad (2)$$

$$A2 = E3\ \sigma_d^{-B2} \quad (3)$$

In the above equations, σ_d and θ are computed directly under the center of the loaded area. θ is computed at the top, middle, and bottom of the base layer. Equations 2 and 3 are then used to adjust the layer stiffnesses from test to design load conditions. The asphalt concrete modulus is also adjusted from test temperature to design temperature.

The design procedure is based on the effective-stiffness concept, in which the existing pavement is characterized by layers with as-built thicknesses but with altered (reduced) layer stiffnesses--i.e., a new pavement with in situ layer stiffnesses as determined from dynamic testing. In the analysis model used, the new pavement is treated as having all its life remaining; consequently, estimation of previous traffic experience is not necessary.

The remaining life of uncracked pavements with in situ stiffness greater than 70,000 psi (482 MPa, the value used to characterize asphalt layers with class 2 cracking) is determined by using ELSYM5 to compute the maximum horizontal tensile strain (ε) at the bottom of the existing asphalt layer and then using this strain to compute N_f (the number of equivalent 18-kip axle loadings to failure, or remaining life) from

$$N_f = 7.56 \times 10^{-12}(1/\varepsilon)^{4.68} \quad (4)$$

Pavements that exhibit class 2 or class 3 cracking (1) or have in situ stiffness (at the test point) less than 70,000 psi (482 MPa) are assumed to have failed; i.e., they are no longer able to withstand additional tensile strains but act as base material providing additional support to the overlay. The critical strain in these cases is at the bottom of the overlay; consequently, ε is calculated at that point.

If the remaining life determined in the previous step is less than the design life, an overlay thickness is projected.

As a result of adding an overlay to the existing pavement, the state of stress experienced by the base and subgrade layers changes. It is therefore necessary to adjust these layer stiffnesses so that they correspond to the changed stresses. The procedure previously outlined is used. Once the layer stiffnesses corresponding to the new stresses have been found, ε is computed--for uncracked pavement, at the bottom of the existing asphalt layer, and for cracked pavement, at the bottom of the overlay--and the remaining life is determined from Equation 4. This procedure is repeated until the remaining life equals the design life.

DESIGN EXAMPLES, COMPARISON OF METHODS, AND MODEL VERIFICATION

Measured deflection data from projects in five states (Utah, Arizona, Ohio, Florida, and California) are analyzed here by using the FHWA-RII overlay design method. The same data are also analyzed by using the California (2), Utah (3), Louisiana (4), and Mississippi (5) overlay design procedures. This comparison of methods is not intended as direct verification of the proposed method; rather, it is included to show that a great variation exists in the methods currently used by various agencies and that the overlay thicknesses derived from the proposed design scheme are not entirely in disagreement with existing practices.

Analysis of Field Data

Measured Dynaflect deflection data taken on 15 projects, at a total of 236 individual test locations, were analyzed. Deflection data were taken before and after placement of an overlay for 10 projects in Utah and Arizona, and the data for Franklin 317 in Ohio were taken after placement of an asphalt base, an asphalt leveling course, and an asphalt surface course. The rest of the projects represent deflection surveys of existing pavements at various stages of deterioration and are included for comparison purposes only.

The computed overlay requirements are summarized in Table 1. The table indicates that the average overlay thicknesses (average of all tests) determined by OAF and by the California method (2) are identical, even though the California procedure totally ignores any temperature effects. However, the test temperatures for the California projects were close to the design temperature. The Utah procedure (3) predicts a slightly higher overlay

Table 1. Summary of overlay thickness as determined by OAF and state procedures.

Project	No. of Tests	AC Thickness (in.)	Avg Overlay Thickness (in.)				
			OAF	California	Louisiana	Mississippi	Utah
American Fork, Utah							
Before	13	3	2.17	0.16	7.08	0.80	0.30
After	3	4	0	0	0.40	0	0
Coalville, Utah							
Before	7	5.75	2.51	1.81	5.93	8.31	0.84
After	3	13.15	0.73	0	3.40	5.23	0.87
Cove Fort, Utah							
Before	12	4	3.45	3.12	9.38	6.07	7.27
After	7	8.2	1.31	3.77	4.86	6.36	2.54
Juab County, Utah							
Before	20	5	2.05	0.67	5.48	6.33	3.48
After	16	7	2.30	3.11	6.59	9.38	5.90
Spanish Fork, Utah							
Before	17	5	1.04	0.00	5.11	0.52	0.00
After	9	9.2	0	0	0	0	0
OH-317, Franklin County							
301	8	6	2.39	1.48	4.89	6.23	2.84
402	19	7.25	0.96	0.11	3.69	3.32	0.97
404	19	8.5	0	0	1.27	0.48	0.02
Dead River, Arizona							
Before	1	7.25	2.3	3.7	5.8	9.0	0.9
After	1	10.5	0	0	4.0	2.9	0
Crazy Creek, Arizona							
Before	1	4	4.3	4.3	9.5	9.7	4.6
After	1	6.25	0	0	2.8	4.2	0.4
Avondale, Arizona							
Before	1	4	0	3.7	5.4	9.0	0.6
After	1	6	0	0.4	5.2	4.9	2.6
Benson, Arizona							
Before	1	7.75	5.2	2.4	4.8	7.2	2.9
After	1	9.5	0	0	2.8	2.8	0
Lupton, Arizona							
Before	1	4	1.5	2.1	4.7	7.6	2.7
After	1	7.5	0	0	6.0	1.6	2.1
I-75, Florida	22	4.5	1.15	0.24	3.31	4.11	1.10
Delaware County Road 72	17	5.5	0.62	0.45	5.32	3.08	1.89
California project 02-616-515-97-CA	19	4.8	0.57	5.81	6.27	9.29	1.08
Butter County, California, cement-treated base	15	3	0.40	1.24	4.67	2.69	0
Avg of all tests			1.28	1.30	4.71	4.39	1.77

thickness than the OAF, but most of this increase is from a relatively small percentage of test locations where the maximum deflection and the shape of the deflection basin indicated reduced subgrade support. Because maximum deflection is sensitive to support values whereas subgrade has a relatively small effect on critical strains, this difference is to be expected.

The Louisiana and Mississippi procedures (4,5) result in substantially thicker overlays than the other three methods. The temperature effect has been ignored in the Mississippi method whereas a temperature adjustment factor [used to adjust measured deflections from test temperature to 60°F (16°C)] is incorporated in the Louisiana design. This factor, however, is inconsistent with those used by other states, appears more appropriate for airport pavements than for thinner highway pavements, and is partly responsible for the thick overlays. Another explanation for the increased overlay thicknesses with these procedures is that both Mississippi and Louisiana have an abundance of weak subgrade, which results in high maximum deflection.

Model Verification

Although no direct evidence for verification exists, some indirect evidence is available. Franklin 317 is currently in good condition after approximately 3 million equivalent axle loads (60 percent of its design life) and should not require an overlay. Delaware County Road 72 is currently in excellent condition after 5 years of service (approximately 35 percent of its design life). It is possible that the 0.6-in. (16-mm) overlay predicted by OAF is adequate for a 20-yr design life. The remainder of the pavement sections analyzed have not been in service long enough for any conclusions to be formed.

A successful overlay design method should be consistent with before and after overlay measurements. It should be able to predict that the required overlay thickness after an overlay has been placed will decrease by the amount of actual overlay; e.g., if the before overlay measurements indicate that a 3-in. (76-mm) overlay is needed and a 2-in. (51-mm) overlay is built, after overlay measurements should indicate the need for an additional 1 in. (25 mm) of overlay. If the overlay effectiveness factor is defined as the ratio of the decrease in predicted overlay (from before and after measurements) divided by the actual overlay, then this factor can be used to judge the success of the method.

The results of this analysis, representing the weighted average of the before and after overlay data (weighted by the number of test locations after overlay) are as follows:

Method	EF	Range
OAF	1.11	0.51 to 2.97
California	0.93	0.08 to 1.91
Louisiana	1.64	-0.37 to 6.68
Mississippi	1.57	-0.07 to 2.51
Utah	0.91	-1.00 to 1.87

The average effectiveness factors for OAF, California, and Utah are close to the expected 1.0, and the range of variation for OAF is not unreasonable. The Louisiana and Mississippi methods both result in substantially higher effectiveness factors and have more variability than the other methods. It should also be noted that the Louisiana, Mississippi, and Utah methods result in negative factors; i.e., the predicted overlay based on after-overlay measurements is greater than that based on before-overlay measurements.

Although the evidence is circumstantial, the results of the above analysis indicate that the proposed method is successful in evaluating the in situ layer properties and in determining the required overlay thicknesses.

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Analysis of Stresses in Unbonded Concrete Overlay

BHAGIRATH LALL AND G. LEES

The results of a laboratory investigation in which static load tests were conducted on unbonded concrete overlays are presented. The investigation included study of the critical stresses and deflections that occur when an unbonded overlay of a concrete slab on subgrade is loaded at corner, edge, and interior positions and static loads are applied through varying contact areas. The distribution of stresses in the two slabs (overlay and underlying), whose ratio of thickness was varied, was investigated. The investigation was conducted on model-scale slabs. The construction material used for the model slabs was a microconcrete with high flexural strength. Concrete overlays are seen as an important means of strengthening existing concrete pavements. The use of multiple-layered systems for the new construction of thick slabs is regarded as an innovation in pavement design. The limitation of existing methods for the design of concrete overlays established the need for the investigation. Load-stress characteristics of the overlay systems are presented, and the effect of the warping of the slabs on these characteristics is analyzed to provide an understanding of the behavior of the pavement. The analysis presented is a forerunner to the establishment of a new method of design.

A laboratory investigation was conducted to study the stresses in an unbonded overlay of concrete pavement. The model slabs, whose dimensions were 3x9 ft (0.92x2.75 m), were constructed of microconcrete on sand subgrade. The stress measurements were made in both the underlying slab and the overlay in the three critical locations--corner, edge, and interior--when static loads were applied in these locations through circular contact areas. The scale of the model slabs was carefully selected not only to ensure simple geometric similarity but also to simulate as closely as possible the theoretical assumptions that can be applied to the analysis of the prototype. The assumptions and the resultant theory developed by Westergaard (1,2) were used to exercise dimensional control over the model in relation to the prototype. The horizontal dimensions of the model slabs were selected to ensure infinite behavior in both directions for the interior loading conditions.

The investigation focused mainly on the unbonded overlay providing frictionless interface to simulate the theoretical assumptions. To keep the friction at the interface of the underlying slab and the overlay as low as possible, an MGA pad was introduced between the two slabs to act as a slip layer. The MGA pad consists of a Melinex Polyester film (gage 100), Molyslip grease (containing 3 percent molybdenum disulphide), and a hardened aluminum sheet 0.003 in. (0.075 mm) thick. MGA pads were used by Hughes and Bahramian (3) to reduce end restraint in cube tests for the determination of uniaxial compressive strength of concrete and were reported to be effective.

The strain gages were fixed to the upper surface of the pavement slabs. Strain gages were so located for all three loading positions to determine maximum principal stresses. In addition, deflection measurements were made along several lines to establish the pattern of bending of the slabs. Unless otherwise specified, all references in this paper to stresses and deflections refer to maximum values for the location of loading under discussion. A hypothesis on the behavior of the overlay-pavement-earth system is presented in this paper, along with a description of the state of stress of an A/B overlay system, which consists of an overlay slab A on an existing slab B resting on subgrade, where A and B have equal or unequal thicknesses. In the following discussion, 1/1 and 1/1.33 overlay systems refer to (a) a 1-in. (25-mm) thick overlay on a 1-in.-thick slab and (b) a 1-in.-thick overlay on a 1.33-in. (34-mm) thick slab on subgrade.

CORNER LOADING OF A/B OVERLAY SYSTEM

In analyzing a single slab on subgrade, Westergaard (1) accounted for the degree of subgrade support in presenting the load-deflection and load-stress relations. That analysis provides corrections to be applied to values computed by using the equations of the original analysis (2). It is necessary to determine certain quantities experimentally in order to compute these corrections.

Teller and Sutherland (4) reported that for various reasons it was not possible to make a satis-