Overlay Thickness Design for Flexible Pavement

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ABSTRACT

An overlay design method for flexible pavement is presented in which both functional and structural types of performance are considered. The method relates the overlay thickness to various types of failure of the overlaid pavement, such as fatigue and low-temperature cracking, rutting, and roughness. The viscoelastic, plastic, and fatigue properties of the pavement materials are considered. The computer program OVERLAY is developed by modifying the FHWA program VESYS-3-A in order to determine the optimum overlay thickness. The method provides a probabilistic solution and allows for the use of different material properties for different seasons. The use of the method is verified by determining the required overlay thicknesses for two typical pavement conditions under typical traffic volumes, material properties, and environmental conditions. The use of the method is justified in view of the rising cost of pavement rehabilitation.

An important part of the U.S. infrastructure is the highway system. The unfortunate fact is that the system is deteriorating in many areas of the country at an alarming rate. New rationally based methods should be developed to upgrade the performance of the existing highway system.

The performance of the overlaid flexible pavement is a function of various distress types such as fatigue cracking, rutting, and roughness. Fatigue cracking is usually controlled by the magnitude of the repeated tensile strain at the bottom of the asphalt-bound layer (1,2). On the other hand, rutting is assumed to be controlled by the subgrade strain (3,4), stresses in the other layers (5), or the strain in the asphalt-bound layer (3). Most methods of overlay design, however, limit the performance of the overlaid pavement to a single design factor such as fatigue cracking, rutting, or roughness. Therefore, each method makes the assumption that, if the specific design factor being considered is adequately controlled, other forms of distress or performance will also be controlled (1). Other methods of overlay thickness design are based on observations and correlations developed for specific pavements that do not necessarily represent pavements under other conditions. These methods are usually restricted to material types, traffic characteristics, and environmental conditions considered in the original investigations.

The performance of highway pavement can be separated into two main parts: functional and structural. Functional performance describes how well the pavement serves the user, whereas structural performance is related to the ability of the pavement to sustain the load. Although the two types of performance are related, there is currently no well-defined relationship between structural distress and functional performance (1). It is important to develop an overlay design method that considers both functional and structural types of performance and relates the overlay thickness to various types of pavement failure during the useful life of the overlay. It is also important to consider the realistic behavior of pavement materials, such as the viscoelastic and plastic properties of various layers and the variation of these properties, and not simply assume linear elastic behavior with one set of deterministic conditions.

OVERLAY THICKNESS

The overlay thickness design method suggested herein evaluates the required overlay thickness, assuming that a decision has been previously taken to provide an overlay. The method considers the functional as well as the structural types of pavement performance. In other words, the trends of the common failure types--cracking, rutting, and roughness--are evaluated throughout the expected useful life of the overlay. The method is based on obtaining an overlay thickness that provides a serviceability index (SI) at the end of the design life of the overlay equal to or higher than a predetermined limiting SI value. The AASHO SI limits (6) or other arbitrary values can be used for this purpose.

In this study the pavement serviceability under various conditions is determined by using the VESYS-3-A computer program developed by FHWA in cooperation with other agencies (7). The current version of this program considers the viscoelastic material properties as well as the plastic and fatigue properties. The program can handle up to seven pavement layers, which can further be increased within the available computer storage memory. In this program strain and deflection responses are computed and used in conjunction with other criteria to predict pavement distress in terms of fatigue as well as low-temperature cracking, rutting, and roughness.

Fatigue cracking is predicted by using a probabilistic Minor's hypothesis. The criterion for fatigue cracking is based on fatigue resulting from the tensile strain at the bottom of the asphalt-bound layer. It is given as

$$C_q(t) = n_q/N_q \quad (1)$$

where

$C_q(t)$ = increment to the crack index resulting from a repetition of loads in the qth incremental analysis period,
n_q = number of axle loads applied to the pavement in the qth incremental analysis period, and
N_q = number of loads to failure under temperature and strain conditions of the qth time interval; that is,

$$N_q = K_{1_q}(1/R_7)^{K_{2_q}} \quad (2)$$

where R_7 is the radial strain response, and K_{1_q} and K_{2_q} are material fatigue properties.

The crack index at any time is obtained by the summation of the incremental crack indices for pre-

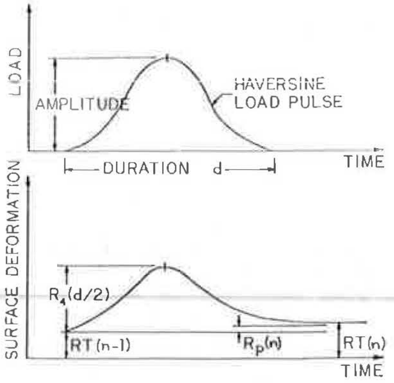

FIGURE 1 Load pulse and pavement deflection response at the nth repetition (7).

vious incremental analysis periods. A crack is initiated at the bottom of the asphalt-bound layer when the expected value of the crack index equals one. The expected area cracked in square feet per 1,000 square feet is further calculated (7).

Rut depth is determined by using viscoelastic-plastic layer theory and repeated load laboratory testing. The wheel load is represented by a haversine pulse, whereas the flexible pavement deflection response curve caused by the nth load repetition takes the form shown in Figure 1 (7). The permanent deformation is represented for each incremental analysis period as

$$R_p(n) = R_4(d/2) \cdot f(n) \qquad (3)$$

where

$R_p(n)$ = permanent deformation at load repetition n,
$R_4(d/2)$ = deflection response of pavement surface as a function of load duration and temperature, and
$f(n)$ = monotonically decreasing function of the number of previously applied loads.

The integration of Equation 3 for various layers over the expected number of load repetitions yields the accumulated rut depth. Therefore, the rut depth is the summation of the permanent deformations of all layers.

On the other hand, slope variance occurs because of the accumulated deformation along the longitudinal profile of the roadway wheelpath, which is assumed to differ because of the randomness of loads, materials, and construction practices. Cracking, rutting, and slope variance are used to define the pavement performance in terms of the life history of the present serviceability index (PSI). The AASHO definition of PSI is used as follows:

$$PSI = PSI_I - 1.91 \log (1 + SV) - 0.01 \sqrt{C} - 1.38(RT)^2 \qquad (4)$$

where

PSI_I = initial serviceability index,
SV = slope variance (10^6 radians),
C = area cracked ($ft^2/1{,}000\ ft^2$), and
RT = rut depth (in.).

A new computer program (OVERLAY) is developed in this study to select the optimum overlay thickness on deteriorated flexible pavements. The VESYS-3-A package, which consists of a main program and a number of subroutines, was included as a part of the OVERLAY program. In this case the original VESYS-3-A main program was converted to a subroutine after minor modifications. During operation the OVERLAY program calls the VESYS subroutine, which in turn interactively calls other subroutines. The program requires the input of the existing layer thicknesses, material properties of the existing layers and the overlay, traffic data, pavement conditions, and environmental conditions, which are summarized as follows:

1. Number of existing layers and layer thicknesses;
2. Properties of materials for each layer, including the overlay, under various environmental

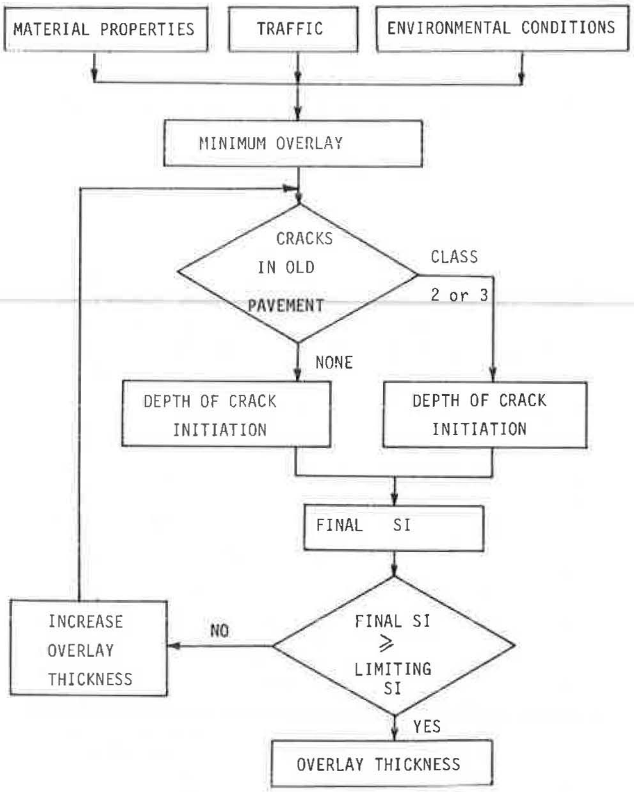

FIGURE 2 Flow diagram for the OVERLAY computer program.

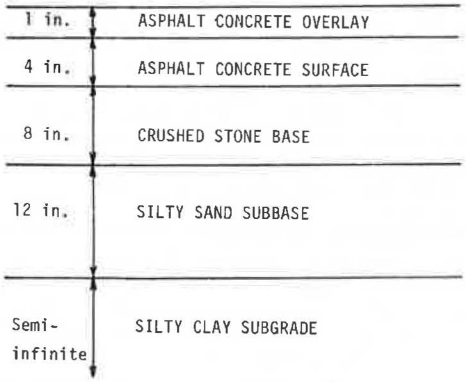

FIGURE 3 Pavement materials and layer thicknesses.

TABLE 1 Material Properties of Asphalt-Bound Layers at Various Seasons When the Existing Surface Layer is Uncracked

	Season			
Material Properties	Winter (40°F)[a]	Spring (60°F)[a]	Summer (85°F)[a]	Fall (70°F)[a]
Modulus (psi)	1,100,000	400,000	100,000	250,000
Poisson's ratio	0.35	0.35	0.35	0.35
Fatigue properties				
K_1	0.158×10^{-4}	0.155×10^{-3}	0.284×10^{-1}	0.932×10^{-3}
K_2	2.94	2.89	2.81	2.86
Permanent deformation properties				
μ	0.04	0.07	0.10	0.08
α	0.75	0.75	0.75	0.75

Note: For the detailed testing procedure, refer to Kenis (7).

[a] Temperature values are the mean temperatures during various seasons.

TABLE 2 Material Properties of Base, Subbase, and Subgrade

Material Properties	Base	Subbase	Subgrade
Modulus (psi)	30,000	15,000	4,000
Poisson's ratio	0.40	0.40	0.45
Permanent deformation properties			
μ	0.04	0.05	0.06
α	0.75	0.75	0.65

Note: For the detailed testing procedure, refer to Kenis (7).

conditions; the material properties are summarized as follows: (a) moduli and Poisson's ratio for all layers, (b) fatigue properties of the asphalt-bound layer, (c) permanent deformation properties for all layers, and (d) coefficients of variation of the material properties for all layers;

3. Pavement condition before overlay, including the cracking class (8);
4. Traffic data in the different seasons, which include (a) expected daily 18-kip equivalent axle loads (EALs) in the design lane throughout the design life of the overlay and (b) tire pressure and radius of tire imprint;
5. Environmental conditions such as the mean temperatures for various seasons;
6. Initial SI after overlaying and limiting SI at the end of the overlay design life; and
7. Desired design life of the overlay.

The OVERLAY computer program evaluates the trend in the individual types of pavement failure after overlaying and combines them by using the serviceability equation. During the evaluation of fatigue cracking, the condition of pavement before overlaying is considered. If no cracks exist in the old pavement, the depth at which the cracks may start after overlaying is assumed to be at the bottom of the old asphalt-bound layer. On the other hand, if the old surface is extensively cracked [AASHO classes 2 or 3(8)], the potential cracks after overlaying are assumed to start at the bottom of the overlay.

An initial minimum overlay thickness of 0.5 in. is assumed, and the SI is calculated and compared with the predetermined limiting SI value. If the SI value at the end of the design life is equal to or larger than the limiting SI value, the overlay thickness is taken as the assumed value. If the SI condition is not satisfied, the overlay thickness is increased by an increment of 0.5 in. and the SI is computed. This process is repeated until the SI condition is satisfied. A flow diagram of the OVERLAY computer program is shown in Figure 2.

EVALUATION OF MATERIAL PROPERTIES

The use of the overlay thickness design method described herein requires the knowledge of various material properties for all layers such as moduli, Poisson's ratios, permanent deformation properties, and fatigue properties of the asphalt-bound layer. Because there is no adequate evidence that nondestructive testing of pavement can provide the necessary material properties, these properties have to be determined in the laboratory. Detailed laboratory procedures for the evaluation of the required material properties are discussed elsewhere (7).

It should be noted that the practical values of overlay thickness vary in increments of 0.5 in. Therefore, the overlay thickness is not sensitive to minor changes in some material properties. Consequently, the method can be simplified by assuming some typical material properties based on the types of materials instead of on extensive laboratory testing. The user can also neglect some failure modes if previous experience indicates that they are not significant for the specific pavement in question. Attention should be also exercised in evaluating the modulus and permanent deformation properties of the existing asphalt-bound layer if cracks are present. Obviously, when the severity of the cracks increases, the material properties change. Therefore, the material properties of the cracked asphalt-bound layer vary between the properties of uncracked asphalt-bound layers and the properties of the base material, depending on the severity of the cracks.

TYPICAL EXAMPLES

A multilane primary road was constructed with four layers and with material types and thicknesses as shown in Figure 3. The material properties of the different layers under different climatic conditions are given in Tables 1 and 2. The old pavement is rutted, and there are no cracks at the surface. The initial 18-kip EAL is 1,000 with an expected traffic growth rate of 3 percent. It is required to determine the overlay thickness so that it will last for 5 years.

The computer program OVERLAY was used to determine the required overlay thickness. In this example the pavement system after overlaying consists of five layers, where the overlay thickness is incrementally increased until the expected SI value at the end of 5 years satisfies the SI limit (2.5 for primary roads). Because the old surface layer is uncracked, the potential cracks after overlaying are

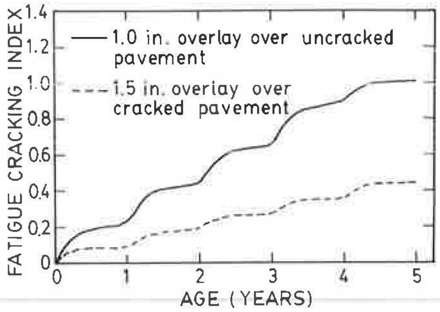

FIGURE 4 Fatigue cracking index versus age for the two pavement conditions.

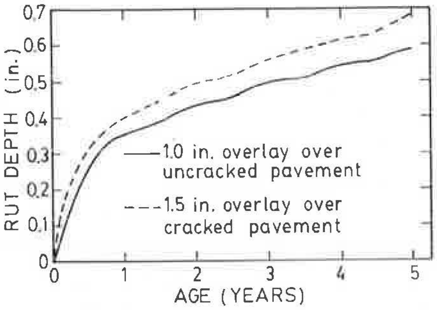

FIGURE 5 Rut depth versus age for the two pavement conditions.

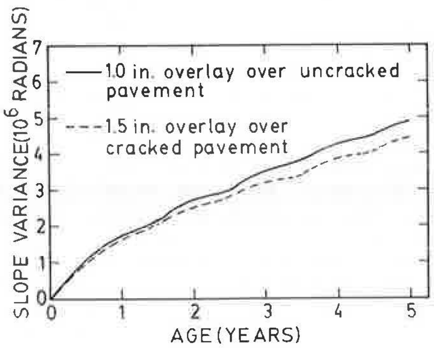

FIGURE 6 Slope variance versus age for the two pavement conditions.

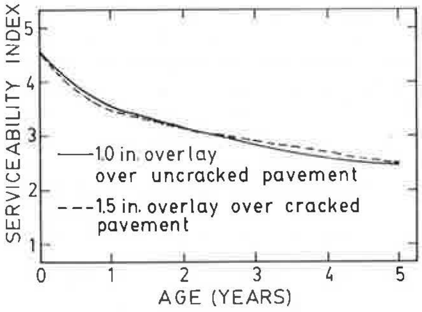

FIGURE 7 SI versus age for the two pavement conditions.

assumed to start at the bottom of the old surface layer. The results indicated that an overlay thickness of 1 in. is required to last for 5 years.

Another example was done with the same conditions as before, except that the existing pavement surface is severely cracked (type 3 cracking) with a modulus value of 38,000 psi. In this case the potential cracks after overlaying are assumed to start at the bottom of the overlay. An overlay thickness of 1.5 in. is needed in this case for a lifetime of 5 years.

The trends of the failure components--fatigue cracking index, rut depth, and slope variance in the two examples--are shown in Figures 4-6. Also, the change in SIs with age is shown in Figure 7. It should be noted that these trends are not uniform because of the change in material properties in various seasons.

CONCLUSIONS

The overlay design method presented herein can consider both functional and structural types of pavement performance and can relate the overlay thickness to various types of pavement failure such as cracking, rutting, and roughness during the design life of the overlay. The method can consider the realistic behavior of pavement materials such as viscoelastic, plastic, and fatigue properties. In this study the computer program OVERLAY has been developed by modifying the FHWA computer program VESYS-3-A in order to determine the optimum overlay thickness. The method described herein allows for the use of different material properties for different seasons, such as a brittle and stiff asphalt-bound layer in the winter, a soft and plastic asphalt-bound layer in the summer, a weak subgrade material during the spring-thaw season, and so forth. Also, because the materials are not always homogeneous, the method considers the random variation in the material properties. In addition, special considerations are available for the variation in traffic loads and volumes such as the use of seasonal load limits during the spring-thaw period.

The use of the method is verified by determining the required overlay thicknesses for two typical pavement conditions under typical traffic volumes, material properties, and environmental conditions. Although the proposed method is sophisticated, its use is justified in view of the escalating cost of highway rehabilitation programs.

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Nondestructive Testing of Pavements Using Surface Waves

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ABSTRACT

A nondestructive method of determining the moduli and thicknesses of pavement systems--the spectral-analysis-of-surface-waves (SASW) method--was introduced in 1982. With this method surface waves containing a wide range in frequencies are generated in the pavement system by impacting the surface. Propagation of the waves through the system is monitored with two receivers located on the pavement surface. By analysis of the phase information for each frequency determined between receivers, Rayleigh wave velocities and wavelengths over the frequency range of interest are determined. Velocity versus wavelength information represents a dispersion curve that on inversion gives Young's modulus profiles along with the thicknesses of the layers. Advancements in the theoretical aspects of the inversion method are presented in this paper. A new, rigorous inversion technique has been developed that is theoretically based and eliminates many of the earlier simplifying assumptions. The versatility and accuracy of the new inversion technique is illustrated by two series of tests that were performed on two rigid pavement sections of an airport runway with different cross-sectional profiles. In addition to being nondestructive, fast, and economical, the SASW method is shown to be capable of detecting thin layers in pavement systems with an accuracy of less than 0.5 in. and finding moduli within about 20 percent, based on comparisons with soil borings and crosshole seismic tests at the same sites. In this regard, no other nondestructive technique has the power and versatility of this method.

Many major highways and airport runways are approaching the end of their serviceable lives. A fast, economical, and precise method for evaluating the properties of these pavements is necessary if meaningful maintenance inspections are to be performed regularly or if overlays are to be designed effectively. The most common nondestructive tests (NDTs) being performed for these purposes are the Dynaflect and the falling weight deflectometer. Although these tests are carried out quite rapidly in situ, in-house data processing can be tedious, and the final solutions are not unique. Another potential deficiency with these methods is that, although a dynamic load is applied to the surface in the field, static elastic theory is employed to reduce the data. Under certain conditions, stress and strain distributions in these dynamic tests can be different from those assumed in the static analyses.

The latest developments in the spectral-analysis-of-surface-waves (SASW) method are discussed herein. The SASW method, which has been under development for some time (1-4), is a nondestructive testing technique that is based on the theory of elastic waves in a layered system. In addition to elastic moduli, layer thicknesses can be determined precisely from the modulus profile. A brief overview of the SASW testing technique is presented herein, followed by recent developments in data analysis that are needed for achieving high-quality Young's modulus profiles and precise layer thicknesses. The results of a case study on two rigid pavement sections using the rigorous data reduction technique are presented to illustrate the value of the SASW method. In conjunction with SASW tests, crosshole seismic tests were performed at each site. Crosshole tests are known as a precise way of determining the stiffnesses of different layers at a site. Young's modulus profiles obtained from these two tests are in excellent agreement, as are the layer thicknesses obtained from the SASW tests and borings.