Extension of the YONAPAVE Method for Determining Flexible Pavements Overlay Thickness from Falling-Weight Deflectometer Deflections

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ABSTRACT

YONAPAVE, a direct and simple method for evaluating the structural needs of flexible pavements, was presented at the 2003 Annual Meeting of TRB (1). The method uses falling-weight deflectometer (FWD) deflection basins to determine the effective structural number and the equivalent subgrade modulus of the pavement-subgrade system independently of the layer thicknesses.

An extension of YONAPAVE is presented to determine the asphalt concrete (AC) overlay required to account also for the fatigue of the AC layer under future traffic loadings. The scheme is based on commonly accepted relationships between AC fatigue cracking and the radial tensile strain at the bottom of the AC layer. The real layered pavement is characterized by an equivalent two-layer system which is determined from the measured FWD deflection basins. Thus, no coring operations are needed since the whole scheme remains basically independent of layers thicknesses.

YONAPAVE algorithms can be solved using a spreadsheet or a handheld PC making it suitable to handle large amounts of data, even in field conditions. The extended method can be used at the network or at the project level for the evaluation of the flexible pavement overall structural capacity and for the calculation of the AC overlay needed to accommodate future traffic based on fatigue considerations. YONAPAVE has been used successfully in numerous pavement evaluation and rehabilitation projects providing reasonable and useful results.

INTRODUCTION

The 1993 AASHTO Guide (2) consolidated the Structural Number (SN) concept for the design of flexible pavements developed based on the findings of the AASHO Road Test in Ottawa, IL nearly 50 years ago. The AASHTO method, however, did not incorporate fatigue in the AC layer as a failure mechanism related to cracking in flexible pavements. Other design methods developed in the 70's and 80's of the last century, like the Shell method (3), the Asphalt Institute method (4) and others, adopted a transfer function relating the radial tensile strains at the bottom of the AC layer to the development of fatigue cracking to determine the thickness of the AC layer required to sustain the traffic demand below the fatigue threshold. This became the basis of the mechanistic (or empirical-mechanistic) pavement design methods based on the multi-layer linear elastic models widely used by many agencies worldwide.

While it has become common practice to back-calculate the moduli of elasticity of 3 to 4 layer systems using FWD measured deflection basins using methods like MODULUS (5), ELMOD (6), and others, the incorporation of the fatigue concept into overlay design of in-service, deteriorated pavements, has not really prospered, though. The inclusion of the back-calculated AC modulus into an overlay design scheme using AC fatigue concepts has many drawbacks: a) the existing AC layer normally has varying types, amounts and severities of distresses (cracking, raveling, oxidation, and others) that affect the continuity and homogeneity of the layer, b) the back-calculated AC modulus is highly dependent on the AC layer thickness which in practice is highly variable even in short sections, and c) the back-calculated AC modulus does not generally agree with the values reported in the laboratory for fresh AC mixtures used in the design phase. The calculation of the AC overlay thickness remains, for the most part, a matter of intuition, judgment, and experience, and is seldom based on the structural evaluation results.

The extended YONAPAVE method presents a practical and simple scheme to calculate the AC overlay thickness required to sustain fatigue cracking due to future traffic based on the FWD structural evaluation results. The effective structural number SN_{eff} and the equivalent subgrade modulus, E_{SG} are determined using the first part of YONAPAVE presented in 2003. For the fatigue analysis, the real pavement-subgrade system is characterized by an equivalent two-layer elastic system. The equivalent thickness and the mechanical properties of the upper layer representing the pavement structure are determined directly from the measured FWD deflection basin, independently of the actual layer thicknesses. It is hypothesized that for the structural evaluation of a flexible pavement, there is no need to characterize the properties of each and every layer but rather its overall structural capacity (represented by SN_{eff}) and the equivalent subgrade support (represented by E_{SG}). The equivalent upper layer obtained from the YONAPAVE analysis constitutes the platform that supports the AC overlay required to sustain fatigue due to future traffic. Using practical guidelines proposed in this paper, the existing or remaining AC layer after milling is combined with a new AC overlay to provide a sound and monolithic AC layer satisfying the fatigue criteria. The extended YONAPAVE method can thus be used at the network or at project level for the evaluation of the AC overlay needed to satisfy both the overall structural capacity of the pavement and the fatigue in the AC layer.

DERIVATION OF YONAPAVE METHOD

YONAPAVE was presented at the 2003 meeting of TRB and published in the TRR journal series (1). The reader is referred to the full paper for complete details. The following sections briefly present the components of YONAPAVE to facilitate its full implementation together with the AC overlay extension presented in this paper.

YONAPAVE departs from the NDT method presented in the 1993 AASHTO Guide for Design of Pavement Structures (2) which assumes the structural capacity of the pavement, represented by the effective structural number – SN_{eff}, is a function of its total thickness and overall stiffness according to the following expression:

$$SN_{eff} = 0.0045 h_p \sqrt[3]{E_p} \quad \ldots [1]$$

where h_p is the total thickness of all pavement layers above the subgrade in inches, and E_P is the effective modulus of pavement layers above the subgrade in pounds per square inch.

YONAPAVE gets around the problem of having to determine h_p by using the Hogg model of a thin slab resting on an elastic foundation of finite or infinite depth to represent the real pavement-subgrade system. Making proper algebraic substitutions, Equation 1 becomes:

$$SN_{eff} = 0.0182 l_0 \sqrt[3]{E_{sg}} \quad \ldots [2]$$

Where l_0 is the characteristic length of the slab in centimeters and E_{SG} is the subgrade modulus of elasticity in megapascals. It is seen from Equation 2 that SN_{eff} is not a function of the total pavement thickness anymore. The problem reduces to the determination of l_0 and E_{SG} from FWD deflection basin interpretation.

The FWD deflection basin is characterized by the deflection basin Area calculated using the following expression (7):

$$\text{Area} = 6(1 + 2\frac{D_{30}}{D_0} + 2\frac{D_{60}}{D_0} + \frac{D_{90}}{D_0}) \ldots [3]$$

where Area is the deflection basin area in inches, and D_0, D_{30}, D_{60}, D_{90} are measured FWD deflections at r=0, 30, 60 and 90 centimeters, respectively.

The relationship between the characteristic length and the deflection basin Area takes the following form:

$$l_0 = A \times e^{B \times \text{Area}} \ldots [4]$$

where l_0 is the characteristic length in centimeters, Area is the deflection basin area defined in equation 3, and A and B are curve fitting coefficients as described in Table 1.

TABLE 1 Curve Fitting Coefficients for Calculation of l_0

Range of Area Values, inches	A	B
Area ≥23.0	3.275	0.1039
21.0≤Area<23.0	3.691	0.0948
19.0≤Area<21.0	2.800	0.1044
Area<19.0	2.371	0.1096

An exponential curve is fitted for the determination of E_{SG} using an expression of the form:

$$E_{sg} = m \times \frac{p}{D_0} \times l_0^{\,n} \ldots [5]$$

where E_{SG} is the Subgrade Modulus of Elasticity in megapascals, D_0 is the measured FWD center plate deflection in microns, p is the pressure on the FWD testing plate in kilopascals, l_0 is the characteristic length calculated from equation 4, and m and n are curve fitting coefficients as shown in Table 2.

TABLE 2 Curve Fitting Coefficients for Calculation of E_{sg}

Range of Area Values, inches	m	n
Area ≥23.0	926.9	-0.8595
21.0≤Area<23.0	1,152.1	-0.8782
19.0≤Area<21.0	1,277.6	-0.8867
Area<19.0	1,344.2	-0.8945

The calculated l_0 and E_{SG} values are plugged into Equation (2) to compute the initial SN_{eff}. This initial value is corrected to account for the Hogg model's thin slab under predictions using the following expression:

$$\text{Corrected } SN_{eff} = 2\ SN_{eff\,(\text{Equation 2})} - 0.5 \quad \ldots [6]$$

Finally, the value obtained with Equation 6 is corrected to a reference temperature of 30 º C using the following expression:

$$SN_T \,/\, SN_{30^\circ C} = 1.33 - 0.011T \quad \ldots [7]$$

where

SN_T = SN_{eff} at any AC temperature.
$SN_{30°C}$ = SN_{eff} at an AC reference temperature of 30° C.
T = AC temperature in degrees centigrade at a depth of 5 cm.

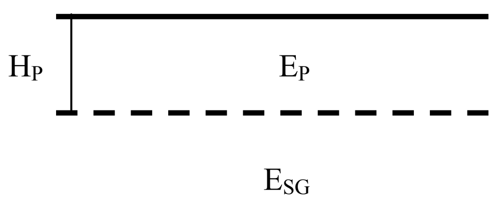
It is possible to develop a temperature correction equation for a different reference temperature other than 30 º C. Equation 7 is applicable to AC layer thicknesses of 10 cm or more. For AC layer thinner than 10 cm there seems to be little effect of AC temperature on SN.

DERIVATION OF THE AC OVERLAY DESIGN SCHEME

Equivalent 2-Layer System and H_P

Consider the two-layer linear elastic system depicted in Figure 1. For the analysis of fatigue in the AC overlay YONAPAVE assumes that the real pavement-subgrade systems can be represented by a simplified equivalent two-layer system whose basic structural parameters, i.e. E_P, E_{SG}, and H_P, can be determined directly from the FWD deflection basin.

FIGURE 1: Equivalent Two-Layer Representation of Pavement-Subgrade System



If the FWD loading plate geometry is applied onto the two-layer simplification of Figure 1, it is found that for a range of H_P thicknesses of 25 to 75 cm the ratio of E_P/E_{SG} is practically independent of H_P, and the following approximation can be adopted:

$$E_P/E_{SG} = 0.1256\ e^{0.2095\ \text{AREA}} \quad \ldots [8]$$

where AREA is the deflection basin area defined in Equation 3.

Since the value of E_{SG} has already been determined using Equation 5, it is possible to evaluate the value of E_P using Equation 8. Finally, the value of the equivalent H_P can be determined plugging the YONAPAVE corrected SN_{eff} (from Equation 6 at the corrected temperature using Equation 7) and E_P into Equation 1. At this point, all the parameters of the equivalent two-layer linear elastic simplification of the real pavement-subgrade system have been determined, together with the effective Structural Number, $SN_{eff.}$

Fatigue of AC Layer

YONAPAVE adopts the relationship proposed by Finn et al (8) and later modified by Uzan (9) to determine the threshold condition for the development of fatigue cracking in the AC layer. This relationship is of the form:

$$\log W_{80} = -3.13 + \frac{h}{380} - 3.291 \log \varepsilon_t - 0.854 \log E_{AC} \;\ldots\; [9]$$

where:

W_{80} = Number of 80 KN (18 kips) ESALs.
h = AC layer thickness in mm.
ε_t = Maximum tensile strain at the bottom of the AC layer.
E_{AC} = Modulus of elasticity of AC at the design temperature in Megapascals.

If it is conservatively assumed that the NDT structurally evaluated pavement has an AC thickness of zero, and that the equivalent H_P represented in Figure 1 equals to the thickness of the granular layer ($H_{GR)}$ in a three layered system, it is possible to compute the minimum AC thickness needed on top of H_P to sustain the future anticipated traffic. The minimum AC thickness to satisfy Equation 9 is calculated with the program JULEA (10) for an AC modulus of elasticity of 3,000 megapascals typical of new AC mixtures at 30 ºC. The modulus of elasticity of the granular layer with thickness H_{GR} (expressed in mm) is determined using the following expression:

$$E_{GR} = E_{SG} (1 + 0.003 H_{GR}) \ldots [10]$$

Where E_{SG} is the subgrade modulus of elasticity determined from YONAPAVE.

Based on theoretical calculations and practical experience gained on numerous evaluation projects it is recommended to divide the flexible pavements into two main groups: a) pavements with H_P below 30 cm, and b) pavements with H_P above 30 cm. For the first group, the calculation of fatigue uses a representative thickness of granular base/subbase of 20 cm. For the second group, the thickness of granular base/subbase is set to 40 cm. Figures 2 and 3 show the minimum required AC thickness for different levels of traffic (expressed in 80 KN ESALs) as a function of E_{SG} for the two groups considered.

From Figure 2, for instance, it is seen that for an E_{SG} of 100 Megapascals and a level of anticipated traffic of $5x10^6$ ESALs, the minimum required AC thickness is 145 mm for pavements with H_P below 30 cm, and about 85 mm for flexible pavements with H_P above 30 cm. The figures also show that as the subgrade support increases, and depending on the traffic levels, fatigue in the AC layer is not an issue anymore and a minimum AC thickness, represented by the horizontal lines, is selected based on construction and/or practical considerations. The question now is how to combine the existing AC layer with the minimum H_{AC} thickness determined using Figures 2 and 3. This is discussed in the following section.

FIGURE 2 Minimum Thickness of AC Layer for Flexible Pavements with H_P below 30 cm.

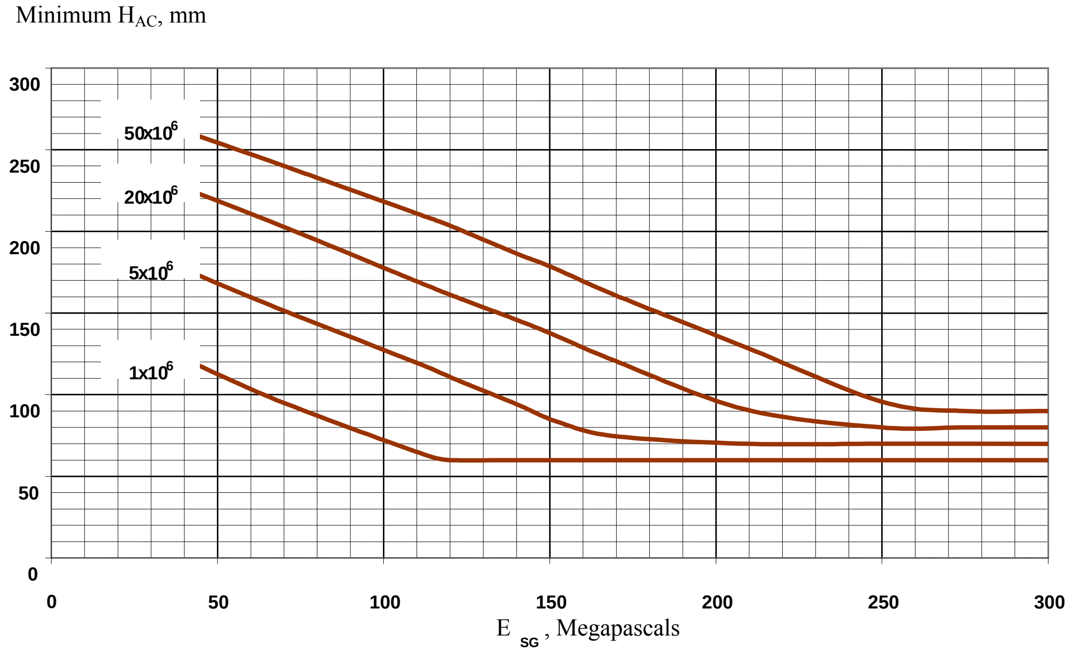
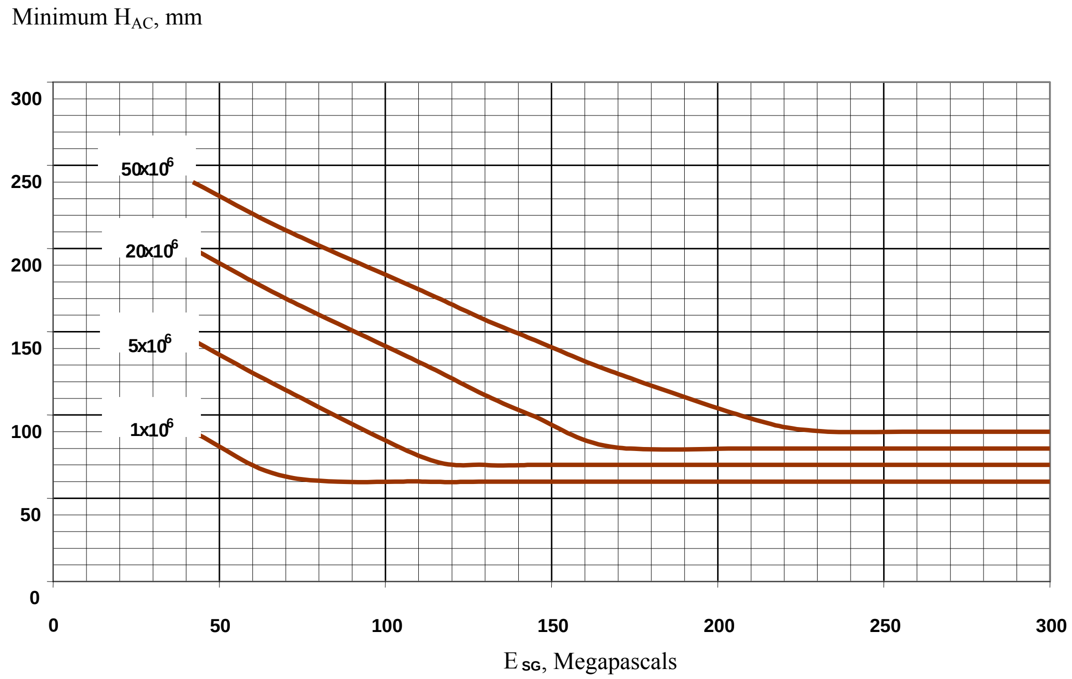


FIGURE 3 Minimum Thickness of AC Layer for Flexible Pavements with H_P above 30 cm



Combining the minimum H_{AC} required with the existing AC layer

A cardinal question in flexible pavement evaluation and rehabilitation is what structural credit can be assigned to the existing AC layer or to the portion of the AC layer remaining after removing part of it by milling. As noted earlier, the thickness of the existing AC layer is variable and thus difficult to determine unequivocally, the AC layer will generally exhibit varying amounts of cracking, weathering, disintegration, etc of varying severities, and the bonding between intermediate AC layers may be partial or nil impairing the bending properties of the layer. It is important to ensure that the existing or remaining AC layer after milling and the new overlay become a monolithic, uniform, and bonded AC layer with a total thickness satisfying the minimum H_{AC} thickness determined using either Figures 2 or 3.

While it is certainly difficult to establish rules to account for each and every case of AC layer deterioration, some general guidelines are proposed in Table 3 for assigning a structural residual value to the existing AC layer based on practical experience and judgment. At this point it is recommended to perform a few shallow boreholes through the AC layer to assess its overall thickness and the bonding between intermediate AC layers. Ground Penetrating Radar (GPR) data could be used instead providing the data are available and reliable.

TABLE 3 Guidelines for assigning structural residual value to the existing AC layer

Case No.	Amount and severity of visible distresses in existing AC layer	Residual value of existing AC layer
1	Severe/medium cracking in over 25% of the pavement area	0 %
2	Cracking in less than 25% of pavement area with low/ medium disintegration and/or oxidation	25%
3	Low/mild cracking and/or other visible distresses	50%

In case No. 1, no structural residual value is assigned to the existing AC layer and the full minimum H_{AC} determined from fatigue considerations using Figures 2 or 3 should be laid anew. In order to minimize reflective cracking onto the new AC overlay it may be feasible in case No. 1 to completely mill and remove the distressed AC layer before placing the overlay, or to lay a bituminous geo-membrane or geo-grid on top of the milled/distressed surface before placing the overlay.

In case No. 2, a residual value of 25% is assigned to the existing AC layer. Thus, an existing layer of 100 mm contributes 25 mm to the AC overlay providing a good bonding can be achieved between the old and the new AC. In a similar way, case No. 3 assigns a residual value of 50% to the existing AC layer, and 100 mm of the existing layer contributes 50 mm to the total overlay required.

IMPLEMENTATION OF YONAPAVE FOR STRUCTURAL EVALUATION AND OVERLAY DESIGN

The implementation of YONAPAVE for flexible pavement structural evaluation and overlay design can be summarized in the following steps:

1. Perform FWD deflection basin measurements using a 45 to 75 KN load level (depending on the legal load limits or design axle in the network). Measure and record AC temperatures at a depth of 5 cm at regular time intervals (once every 1 to 2 hours).
2. Explore and decide whether it is reasonable to divide the evaluated section into uniform subsections based on the longitudinal variation of the maximum FWD deflection and/or AREA, and/or distress/PCI distribution, etc.
3. Compute l_0 and E_{SG} using Equations [4] and [5], respectively.
4. Calculate the initial SN_{eff} using Equation [2], and correct it using Equation [6].
5. Make SN_{eff} temperature corrections using Equation [7].
6. Determine design values. Use a 10^{th} to 30^{th} percentile for E_{SG} and for corrected SN_{eff}. The selected percentiles depend on the importance of the road analyzed. Use the lower percentiles for the major roads and arteries. These lower percentiles also reflect AASHTO recommendation to use reduced values of E_{SG} when these are determined from NDT back-calculation analysis.

The structural adequacy of the evaluated pavement is verified using the following scheme:

1. Estimate future traffic demand in terms of 80 KN (18 kips) ESALs during the design period (10 to 20 years depending on budget or rehabilitation strategies).
2. Using the E_{SG} evaluated with YONAPAVE and the future traffic forecast, determine the required SN based on the 1993 AASHTO Guide (1).
3. Compare the future required SN_{req} with the evaluated corrected SN_{eff} to establish structural adequacy or deficiency. It is convenient to express the structural condition using the Structural Coefficient Index (SCI) which is calculated using the following expression:

$$SCI = \frac{SN_{eff}}{SN_{req}} x100 \quad \dots [10]$$

4. When the SCI is higher than 100%, there is no structural deficit in the pavement. If the SCI is lower than 100%, it is possible to express this deficiency in terms of required AC overlay thickness using the following expression:

$$h_{AC} = (SN_{req} - SN_{eff}) / a_{ol} \quad \dots [11]$$

Where:

h_{AC} = Thickness of AC overlay, inches
a_{ol} = Structural coefficient for the AC overlay (from AASHTO guide or other)

The evaluation of the AC overlay based on fatigue considerations is done according to the following steps:

1. Determine E_P and H_P using Equations 8 and 1 and the SN_{eff} determined in the structural evaluation phase.
2. Determine the minimum required AC overlay to satisfy the future ESALs using Figures 2 or 3 depending on H_P and E_{SG}.
3. Evaluate the structural residual value of the existing AC layer using the guidelines in Table 3.
4. Adopt an AC overlay thickness that satisfies both the structural and the fatigue analysis taking into account the residual value of the existing AC layer and other construction or practical considerations.

5. Perform pre-overlay operations as needed, like deep patching of highly distressed areas, milling, placing a geo-membrane or geo-grid to reduce reflective cracking, etc, before laying down the adopted AC overlay.

EXAMPLES OF YONAPAVE RESULTS

TABLE 4 shows data for 7 Israeli in service-road sections used to exemplify the use of YONAPAVE. Note in the table the variability of the thicknesses reported from coring which illustrates the difficulty in selecting a unique value for the layers thicknesses.

TABLE 4 Road Sections Data

Road No.	Section Length (km)	Total No. Of Cores	Range of thicknesses from coring, cm			Subgrade AASHTO Classification
			AC layer	Granular layers	Total	
4	5.5	11	13-28	25-44	45-70	A-3
90	7.0	29	8-20	5-72	15-80	A-2-7
60	2.0	8	15-33	17-115	40-130	A-7-6
2	2.0	9	9-13	35-65	45-80	A-3
73	5.7	22	20-50	20-85	50-120	A-7-6
767	2.5	10	12-17	0-55	15-70	A-7-6
MB	1.0	8	8-18	22-90	35-110	A-2-4, A-7-6

TABLE 5 shows the results of the FWD deflection basin parameters and the traffic estimate for a 10-year rehabilitation period expressed in 80 KN ESALs.

TABLE 5 FWD Deflection Basin parameters and future anticipated traffic

Road No.	Average D_0, µm	Average AREA, inches	80 KN ESALs
4	290	20.3	$33.1x10^6$
90	390	19.0	$13.8x10^6$
60	455	24.1	$11.0x10^6$
2	340	20.3	$49.6x10^6$
73	330	23.7	$7.4x10^6$
767	665	21.1	$3.7x10^6$
MB	640	20.7	$16.5x10^6$

TABLE 6 shows the results of the YONAPAVE analysis for overall structural adequacy and fatigue of the AC layer.

TABLE 6 YONAPAVE Results

Road No. (1)	30th Percentile $E_{SG,}$ MPa (2)	10th/30th Percentile SN_{eff} (3)	Equivalent H_P, cm (4)	SN_{REQ} (5)	SCI % (6)	AC Overlay required (in mm) based on: SN deficit (7)	AC fatigue (8)	Adopted AC Overlay (in mm) (9)
4	245	3.9	32	3.5	111	0	90	70
90	164	3.1	32	3.5	89	25	80	80
60	82	4.7	43	4.3	109	0	140	110
2	186	3.4	31	4.1	83	40	120	90
73	110	5.2	45	4.0	130	0	80	60
767	86	3.6	40	3.6	100	0	100	100
MB	92	3.2	36	4.4	73	70	130	130

Column 2 of Table 6 shows the 30th percentile values of E_{SG} calculated using Equation 5 after computing l_0 from Equation 4 for the corresponding values of FWD area and D_0.

Column 3 displays the 10th or 30th percentile of SN_{eff} calculated using Equation 2, and then corrected using Equations 6 and 7. The 10th percentile was chosen for the one and two digit road numbers that indicate the higher hierarchy of the road in the network. The 30th percentile was applied in roads 767 and MB.

Column 4 shows the equivalent H_P computed using Equations 8 and 1. As noted, all sections in Table 6 display an H_P value above 30 cm.

Column 5 displays the required SN calculated using the 1993 AASHTO guide for the future traffic listed in Table 5, the subgrade modulus listed in column 2, using 90% reliability and a serviceability loss of 1.5 for the higher ranked roads and 2.0 for the lower ranked roads.

Column 6 shows the Structural Condition Index – SCI computed using Equation 10. Sections with an SCI below 100% suffer from a structural deficit which is expressed in millimeters of asphalt in column 7. This overlay is calculated from the difference between the required SN in Column 5 and the effective SN in Column 3 using Equation 11 for an AC structural coefficient of 0.44 (for SN expressed in inches).

Column 8 displays the minimum AC overlay required to satisfy AC fatigue obtained from Figure 3 using the calculated E_{SG} and the traffic levels shown in Table 5.

The final step consists in adopting an AC overlay that satisfies both the structural deficiency and the AC fatigue considerations, incorporating also construction constraints or preferences, and implementing the guidelines in Table 3 to consider the residual value assigned to the existing AC layer.

To illustrate this final step consider road No. 2 with an existing AC layer of 90 to130 mm (see Table 4). The AC layer condition corresponds to case 3 in Table 3, and thus the layer has a residual value of 50%. Due to construction considerations it was decided to mill the upper 40 mm, leaving an AC layer of 60 to 90 mm with an assigned residual value of 30 mm (50% of 60 mm). Since the fatigue analysis calls for a minimum thickness of 120 mm, a 90 mm overlay in two layers of 50 and 40 mm was placed on top of the milled pavement with a residual value of 30 mm, resulting in a monolithic layer of at least 120 mm as needed. This overlay also satisfies the structural deficit of 40 mm. In a similar way, the adopted overlay shown in column 9 was determined for the other sections in Table 6.

SUMMARY AND CONCLUSIONS

The YONAPAVE method for the evaluation of the structural needs of flexible pavements based on FWD deflections was extended to incorporate the analysis of fatigue in the AC overlay. This extension departs from mechanistic-empirical concepts used in pavement design methods based on linear elastic multilayer models.

YONAPAVE can be used to determine the effective Structural Number SN_{eff} and the equivalent subgrade modulus of elasticity E_{SG} directly from the FWD deflection basins independently of the layer thicknesses. It is based on the interpretation of measured FWD deflection basins using the Hogg model of a thin slab resting on an elastic subgrade, incorporating a correction factor to overcome the thin slab neglect of deflections within the pavement structure. The fatigue analysis is performed on an equivalent two-layer elastic system representing the real pavement-subgrade. The parameters of this two-layer simplification are directly obtained from the measured FWD deflection basin parameters, and thus, the whole method is basically independent of layer thicknesses. The independence of YONAPAVE from layer or pavement thickness is the major innovation relative to other structural evaluation and overlay design methods.

Practical guidelines are presented for assigning a residual structural value to the existing AC layer or to the portion of the AC layer remaining after milling which are based on the amount and severity of visible distresses. For this phase, it is convenient to perform a few shallow AC cores to assess the existing AC layer thickness and the quality of bonding among intermediate layers, or use GPR data if they are available and reliable.

YONAPAVE's simple and practical algorithms can be easily solved using a spreadsheet or a handheld PC making it useful for handling large amounts of data, even in field conditions. YONAPAVE has been implemented in numerous structural evaluation projects in Israel and overseas providing reasonable results for the calculation of the AC overlay needed due to structural deficiencies or provide adequate fatigue resistance to sustain future traffic demand.

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