Concepts for Developing an NDT-Based Design Procedure for Determining Asphalt Concrete Overlay Thickness

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Preliminary flexible pavement asphalt concrete (AC) overlay design concepts using nondestructive testing (NDT) data are presented. The NDT data inputs are equivalent 9-kip wheel load deflections. The maximum deflection and a deflection basin parameter called AREA are used. 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 determination of overlay thickness are proposed. The ILLI-PAVE structural model and resilient materials and soils testing principles are used in the procedure.

The preliminary asphalt concrete (AC) overlay design concepts presented in this paper are based primarily on data and findings from several previous University of Illinois and Illinois Department of Transportation (DOT) research studies and reports (1-5). The procedure is directed toward the determination of the appropriate AC overlay thickness.

The proposed overlay design procedure, which is based on nondestructive testing (NDT), includes four major phases: (a) a field evaluation and condition survey, (b) NDT testing, (c) NDT data interpretation, and (d) determination of AC overlay thickness.

Tentative guidelines and procedures for conducting overlay design are presented in this paper. Conventional flexible pavements (surface treatment + granular base and AC surface + granular base) and full-depth AC sections are considered. It is anticipated that modifications or refinements will be made during any implementation activities.

Although references are made in this paper to Illinois DOT practices and procedures, the proposed overlay procedure is not an approved policy or procedure of the Illinois DOT.

FIELD EVALUATION AND CONDITION SURVEY

Condition Survey

Condition survey and distress identification activities should (at a minimum) document the degree of cracking and rut depth. Comprehensive pavement condition survey methodologies have been developed by many agencies. For example, the Illinois DOT has a standard procedure for conducting routine flexible pavement condition surveys.

General Information

It is desirable to develop general information input on the pavement and its surroundings. This information is particularly helpful in the process of selecting design sections. The development of general information should include the following:

1. Note cut and fill areas,
2. Provide pedologic soil series data,
3. Determine drainage conditions, and
4. Comment on the uniformity of the pavement's present condition.

Input data for item 3 (drainage conditions) are the depth of the ditch bottom below the pavement edge and the U.S. Department of Agriculture (USDA) internal soil drainage class. The internal soil drainage classes are (a) very poorly drained, (b) poorly drained, (c) imperfectly drained, (d) moderately well drained, (e) well drained, (f) somewhat excessively drained, and (g) excessively drained. (Soil series and internal drainage class data are provided in the standard USDA County Soil Report.)

NDT TESTING

The ILLI-PAVE analyses used in the development of the NDT evaluation procedure and the AC overlay thickness design concept are based on pavement responses under a moving 9-kip wheel load. Soil, crushed stone, and AC material properties and structural sections considered in the basic ILLI-PAVE study are described elsewhere (2,3,5).

Pavement structural responses are determined from NDT pavement surface deflection measurements. The NDT deflection basin is characterized by the following terms:

D0 = maximum deflection (center of plate);
D1, D2, D3 = deflections at 1, 2, and 3 ft from the center of plate; and
AREA = deflection basin area (in.) (see Figure 1), defined as AREA = 6[1 + 2(D1/D0) + 2(D2/D0) + (D3/D0)].

AREA combines the four sensor deflections. It varies from 11 in. (Boussinesq approximation) to 36 in. (maximum by definition). Stiffer pavements have larger areas. In this paper, Δ and AREA are used to describe responses to moving 9-kip wheel loads.

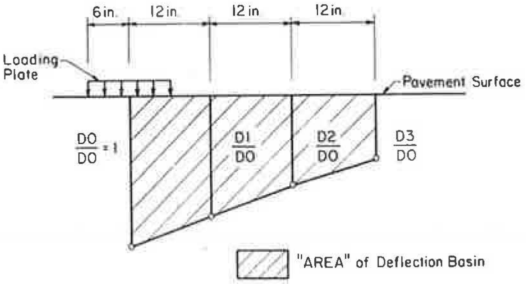
The NDT data must simulate or be correlated with a 9-kip moving wheel load response. A comprehensive Illinois study (2,3) concluded that the falling weight deflectometer (FWD) was an excellent device. Center-of-plate deflection and deflection basin area for 9-kip FWD loading (12-in.-diameter plate) are considered equivalent to moving 9-kip wheel load responses.

Responses measured by the Illinois DOT road rater can also be correlated with the 9-kip moving wheel load responses (2), as shown below:

$$\Delta = 1.36\,DO_{RR} - 3.8 \qquad R^2 = 0.94 \quad SEE = 3.2 \qquad (1)$$

where Δ is the equivalent 9-kip moving wheel load deflection (in mils) and DO_{RR} is Illinois DOT road

Figure 1. Deflection basin characterization.



rater center-of-plate deflection (8-kip peak-to-peak loading, 12-in.-diameter plate, 15 Hz) (in mils).

$$\text{AREA} = 1.19\ \text{AREA}_{RR} - 7.6 \qquad R^2 = 0.95 \quad \text{SEE} = 1.1 \qquad (2)$$

where AREA is the equivalent 9-kip moving wheel load deflection basin area (in inches) and AREA_{RR} is the Illinois DOT road rater (8-kip peak-to-peak loading, 12-in-diameter plate, 15 Hz) deflection basin area (in inches).

If possible, the NDT testing should be done during the spring period (March and April in Illinois). NDT testing at several times during the year can be used to establish a seasonal-effect pattern. NDT should not be done when any of the paving materials or the subgrade is frozen. NDT should be conducted in the outer wheelpath of the traffic lane being evaluated.

Because NDT tests can be conducted quickly, it is easy to obtain frequent measurements. It has been proposed (1) that NDT test sites be spaced at 100 ft for rolling terrain, numerous cut-and-fill transitions, and pavements with extensive distress. For level terrain with uniform soil conditions, the test sites should be spaced at 200-ft intervals. On two-lane facilities, the test locations can be staggered in the adjacent lanes to provide more complete longitudinal coverage. It is important to record the temperature of the AC layer at frequent intervals (approximately every hour) during NDT testing.

NDT DATA INTERPRETATION

The following general procedure is suggested for manipulating and interpreting the NDT data.

Data Reduction and Presentation

1. Reduce the NDT data in terms of Δ and AREA.
2. Prepare a plot of Δ and AREA versus longitudinal distance along the pavement.
3. Compute Δ and AREA statistics (averages, standard deviations, coefficients of variation).

A FORTRAN 5 computer program has been developed to reduce and plot the data (1).

Design Section Determination

1. Consider the condition survey data, Δ, and AREA plots and statistics.
2. Determine whether the project can justifiably be subdivided into more than one design section. If the Δ coefficient of variation is greater than approximately 20 percent, more than one design section should be established.
3. Establish Δ and AREA design section inputs by road class (Illinois DOT nomenclature) as follows: for class 1 (four-lane facility) and class 2 ($\text{ADT} > 1{,}000$) roads, the design section inputs are $\Delta + 2\sigma$ and $\text{AREA} - 2\sigma$; for class 3 ($400 < \text{ADT} < 1{,}000$) and class 4 ($\text{ADT} < 400$) roads, the design section inputs are $\Delta + 1\sigma$ and $\text{AREA} - 1\sigma$.

Evaluation of Existing AC Layer

If the AC layer displays class 2 cracking (according to the AASHO Road Test definition, class 2 AC cracking has progressed to the stage where the cracks are connected together to form a grid pattern), it is not considered an AC layer but a granular material layer. If the existing AC layer is treated as a granular layer, the AC overlay is designed separately (critical AC layer radial strains are at the bottom of the AC overlay).

Back-Calculation of Layer Properties

Back-calculation procedures should be applied to each design section. The back-calculation input values are the equivalent 9-kip moving wheel load responses (Δ and AREA).

Selection of Equations

The first step is to select the proper nomographs or algorithms (surface treatment + granular base, AC surface + granular base, or AC surface + AC base).

Conventional Flexible Pavement

Δ and AREA regression equations for three different groups of conventional flexible pavements (AC surface + granular base) with variable thickness of

Figure 2. ILLI-PAVE deflection basin algorithms for conventional flexible pavements.

Dependent Variable	R^2 (%)	SEE	Constant O	Eri p	E_{AC} q	T_{AC} r	Tgr s
Group 1: $1.5 \leq T_{AC} \leq 3''$ $\quad 4 \leq \text{Tgr} \leq 12''$							
Log Δ	92.5*	0.04	2.096	-0.0232	-0.000149	-0.0967	-0.0137
AREA	90.6*	0.78	11.18	-0.315	0.00237	1.742	0.187
Group 2: $3 \leq T_{AC} \leq 5''$ $\quad 4 \leq \text{Tgr} \leq 24''$							
Log Δ	94.6*	0.04	1.878	-0.0203	-0.000194	-0.0372	-0.00694
AREA	93.4*	0.84	13.25	-0.353	0.00383	1.040	0.0958
Group 3: $3 \leq T_{AC} \leq 8''$ $\quad 6 \leq \text{Tgr} \leq 18''$							
Log Δ	95.5*	0.04	1.900	-0.0197	-0.000200	-0.0451	-0.00707
AREA	92.6*	1.07	13.21	-0.359	0.00409	0.946	0.127

* Significant at 1% level

Equation of the form:

$$\text{Dependent Variable} = 0 + p \times \text{Eri} + q \times E_{AC} + r \times T_{AC} + s \times \text{Tgr}$$

Variable	
E_{AC} (ksi)	Modulus of Elasticity of AC Layer
Eri (ksi)	Subgrade Modulus at Intercept
T_{AC} (in.)	Thickness of AC layer
Tgr (in.)	Thickness of Granular Base
Δ (mils)	Equivalent 9 kip Moving Wheel Load Deflection
AREA (in.)	Equivalent 9 kip Moving Wheel Load Deflection Basin Area

AC (T_{AC}) and crushed-stone granular base (T_{gr}) are shown in Figure 2. Nomographic solutions for the equations are given elsewhere (2). Because T_{AC} and T_{gr} are known, the Δ and AREA equations can be used to determine E_{AC} and E_{ri}. Figure 3 is used to determine E_{ri} for pavements with AC surface and granular base.

Full-Depth AC Pavement

The nomographs shown in Figure 4 are used to determine E_{AC} and E_{ri} for full-depth AC pavement sections. The required inputs are Δ and AREA (9-kip equivalent moving wheel load responses). T_{AC} is the total AC thickness (surface + base). Interpolate for thicknesses not covered by Figures 4 to 8.

The following equation is used to determine the pavement thickness required to achieve a desired surface deflection:

$$\text{Log}\,\Delta = 3.123 - 0.0273\,E_{ri} - 0.895\,\text{Log}\,T_{AC} - 0.359\,\text{Log}\,E_{AC} \qquad (3)$$

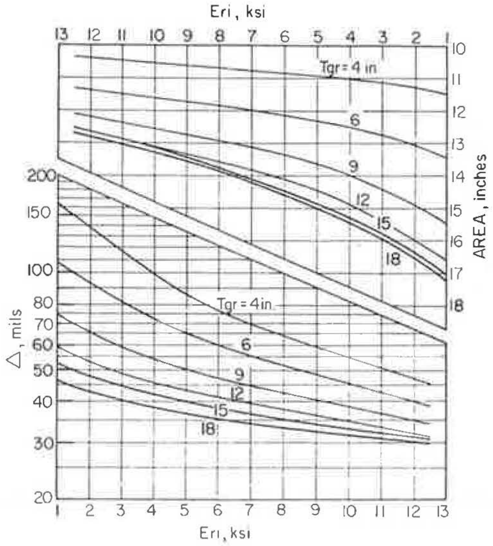
where

E_{ri} = resilient modulus (ksi),
T_{AC} = thickness of asphalt concrete (surface + base) (in.),
E_{AC} = asphalt concrete modulus (ksi),
R^2 = 0.98, and
SEE = 0.0335.

Determination of Moduli

The next step is to determine E_{AC} and E_{ri}. E_{AC} is the modulus of elasticity for asphalt concrete, and E_{ri} is the resilient modulus of cohesive subgrade soil. A typical plot of resilient modulus versus repeated deviator stress is shown in Figure 5. The plot typically displays a "break point" deviator stress where there is a substantial change in the slope of the $E_R - \sigma_D$ relation. The resilient modulus and deviator stress corresponding to the break point are E_{ri} and σ_{Di}, respectively. Extensive testing of typical fine-grained Illinois soils indicates that σ_{Di} is approximately 6 psi. E_{ri} is closely approximated by the resilient modulus at a repeated deviator stress level of 6 psi (4).

Figure 3. Evaluation nomograph for surface-treated pavements.



If appropriate AC mix data are available, it is possible to estimate E_{AC} by using various procedures (6,7). A calculated E_{AC} mixture temperature relation (0.020-sec loading time) for a typical Illinois DOT high-design-type AC mixture is shown in Figure 6. The data are typical for initial asphalt penetrations of 90 to 120, approximately 5 percent asphalt content, and void contents of 1.75 to 2.0 percent. Similar relations can be easily developed for other asphalts and mixture compositions. There may be cases in which resilient testing of AC field cores is justified to establish a relation between E_{AC} and mixture temperature.

Selection of Value for Use in Design

Based on a consideration of the available E_{AC} data (NDT back-calculation, estimation, and laboratory testing), select an appropriate value for subsequent use in the overlay design.

OVERLAY DESIGN

Transfer Function Concepts

Implicit in the proposed overlay design process is the assumption that pavement response parameters (stresses, strains, and deflections) can be used to predict pavement performance. The most widely used flexible pavement transfer functions are based on surface deflection, subgrade compressive strain, and radial (flexural bending) strain at the bottom of the AC layer.

A strong relation exists between the fatigue behavior of the AC layer and surface deflection. Significant correlations between surface deflection (Δ) calculated by using the ILLI-PAVE model and AC radial tensile strain (ϵ_{AC}) have been developed for conventional flexible pavements (AC layer + granular base and subbase) and full-depth AC pavements (1). The relations are shown in Figures 7 and 8. The AC fatigue relation shown in Figures 7 and 8 (based on ϵ_{AC}) is considered to be representative of Illinois DOT high-design-type AC mixtures.

If the field evaluation data indicate that the subgrade has not significantly contributed to any rut depth development noted in the pavement, excessive subgrade stress and/or strain is unlikely. The addition of the AC overlay will further reduce subgrade stress and strain levels. Statistical analyses of ILLI-PAVE data for conventional flexible pavements and full-depth asphalt sections indicate a highly significant correlation between surface deflection and subgrade compressive strain. Thus, a surface deflection design criterion also, in effect, considers subgrade strain.

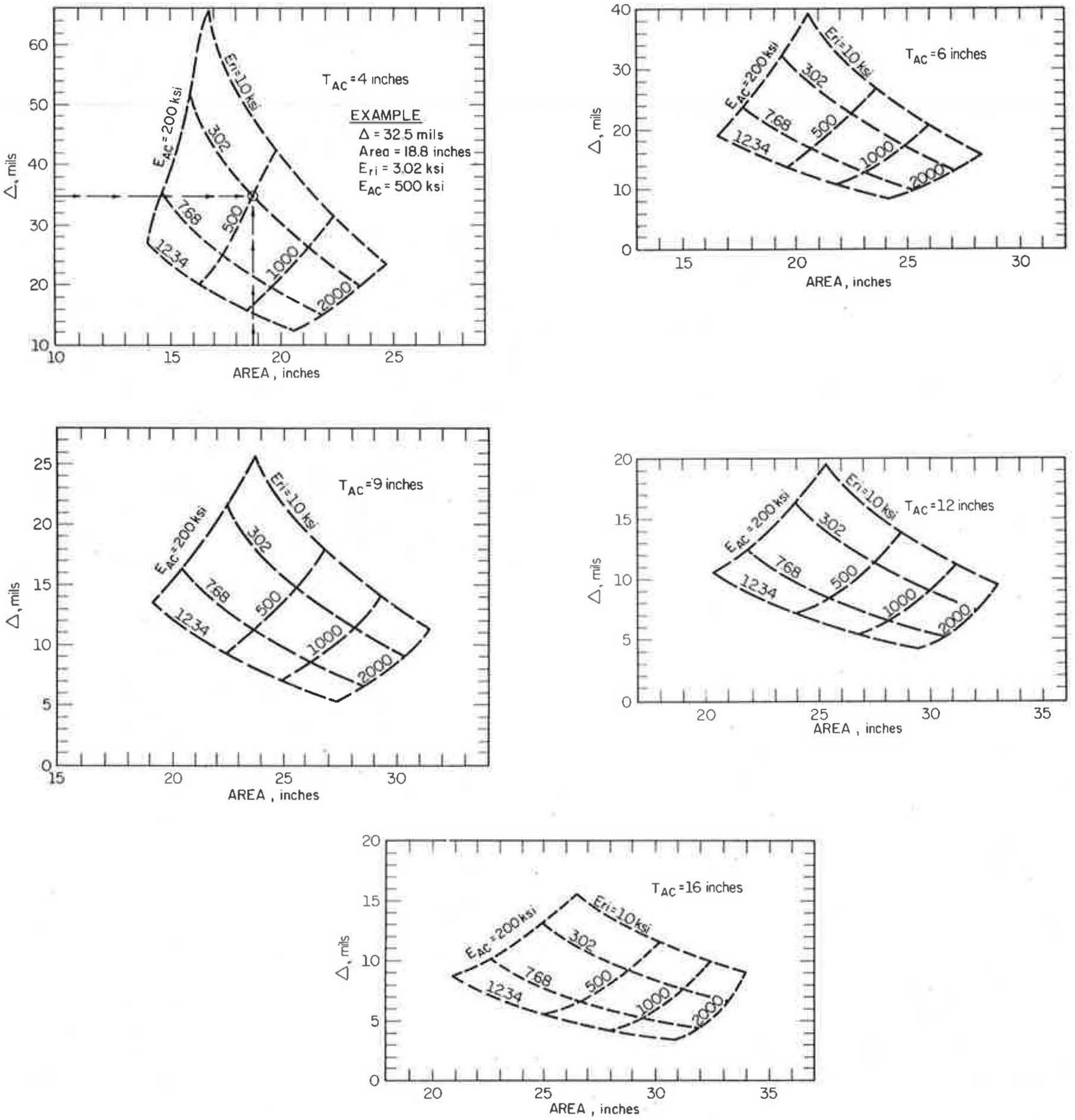
It is recommended that surface deflection criteria be used for conventional and full-depth asphalt concrete flexible pavements during initial implementation activities. Surface deflection can be calculated more accurately than radial strains. Surface deflection is also a response parameter that can be easily measured whereas AC radial strain measurements are more difficult to make.

Design Input Information

Two time periods--spring (March and April) and summer-fall (all other months)--are considered. Thus, two sets of design input information are needed for the subgrade and AC materials. The procedure followed is outlined as follows:

1. Establish AC overlay design temperature(s) by using the following steps: (a) select the weighted mean monthly air temperature (WMMAT) from Figure 9

Figure 4. Evaluation nomographs for full-depth AC pavement for various total AC thicknesses.



(this value is applicable for the summer-fall period, i.e., the months of May through February); (b) enter Figure 10 with the WMMAT from step a and determine the weighting factor (WF); (c) calculate the WF for the spring period, i.e., March-April (spring WF = 0.36 WF); (d) from Figure 10 determine the WMMAT for a value of 0.36 WF (this temperature value is appropriate for the spring period); (e) enter Figure 11 with the appropriate values of WMMAT (for spring and summer-fall) to determine the AC mix temperatures; (f) determine E_{AC} from Figure 6; and (g) to adjust the asphalt concrete modulus (E_{AC}) for a different temperature, multiply the reference modulus (for a given temperature) by the ratio of the F-values from Figure 12 [ratio = F(new temperature)/F(reference modulus temperature)]. The approach is based on the concepts proposed in the Shell procedure (8). The temperature data were established based on an analysis of average Illinois conditions.

2. Adjust the E_{AC} value determined from NDT data interpretation for spring and summer-fall temperatures (the procedure outlined in item 1).

3. Establish E_{AC} for the overlay mix for spring and summer-fall design temperatures. The E_{AC} values can be based on laboratory testing or predicted (as is the case for Figure 6).

4. Consider the E_{AC} of the existing AC layer and the overlay mix and select spring and summer-fall E_{AC} values for the combined thickness of the existing AC layer and the AC overlay. If the ratio of E_{AC} values (overlay mix to existing AC) is less

Figure 5. Resilient modulus versus deviator stress for fine-grained soils.

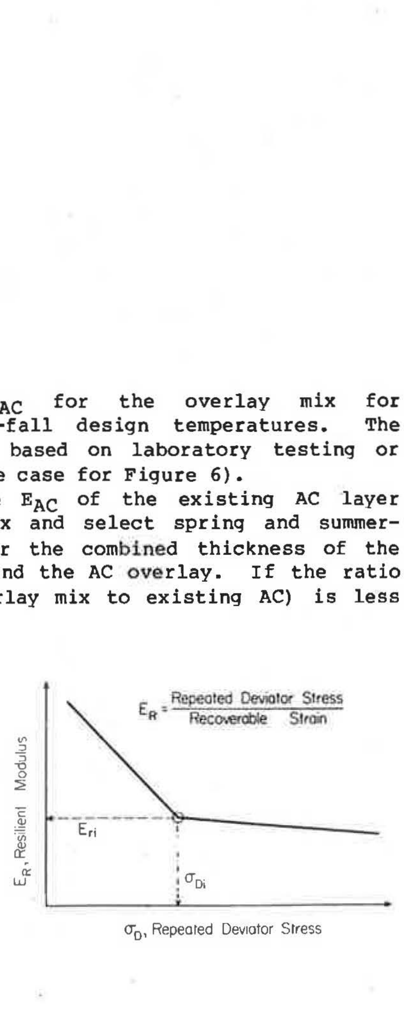


Figure 6. AC mixture temperature versus AC modulus for typical Illinois class 1 mix.

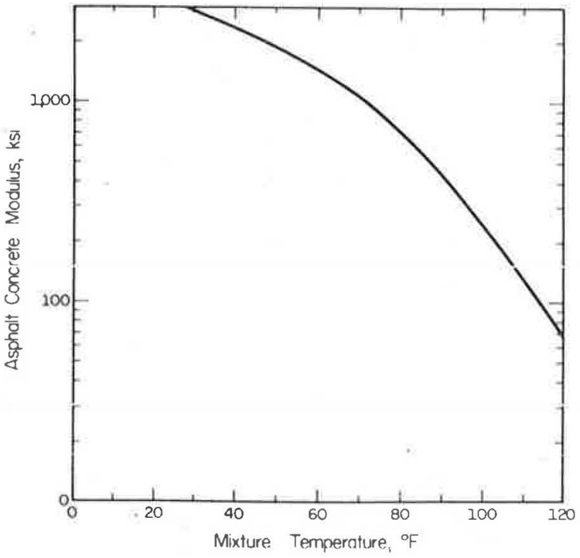


Figure 7. Surface deflection versus AC radial strain life for conventional flexible pavements.

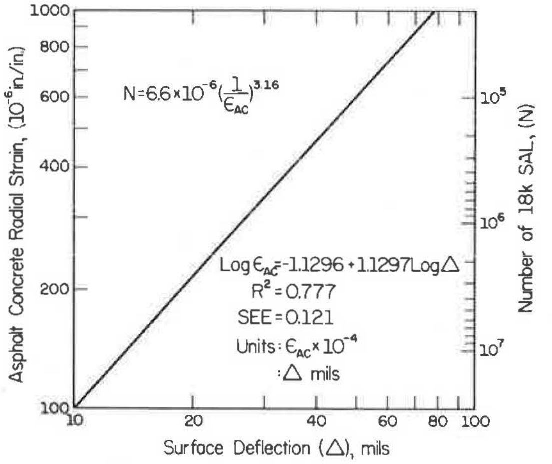


Figure 8. Surface deflection versus AC radial strain life for full-depth AC pavements.

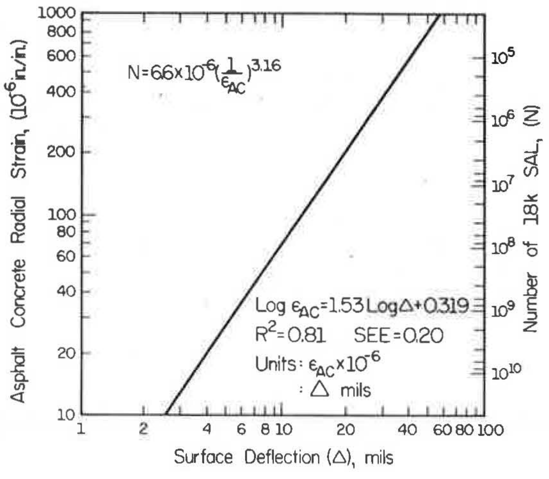


Figure 9. WMMAT data for Illinois.

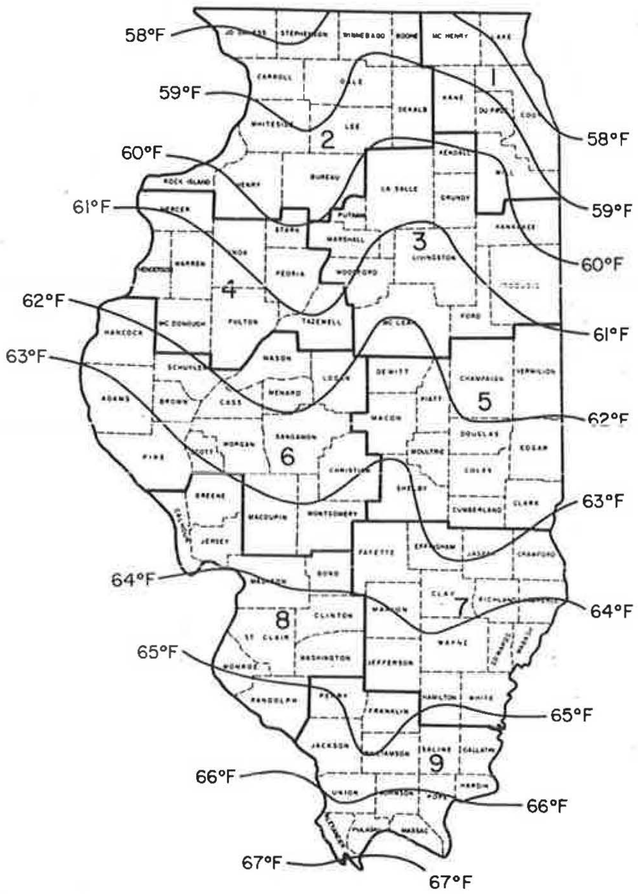


Figure 10. WMMAT versus WF.

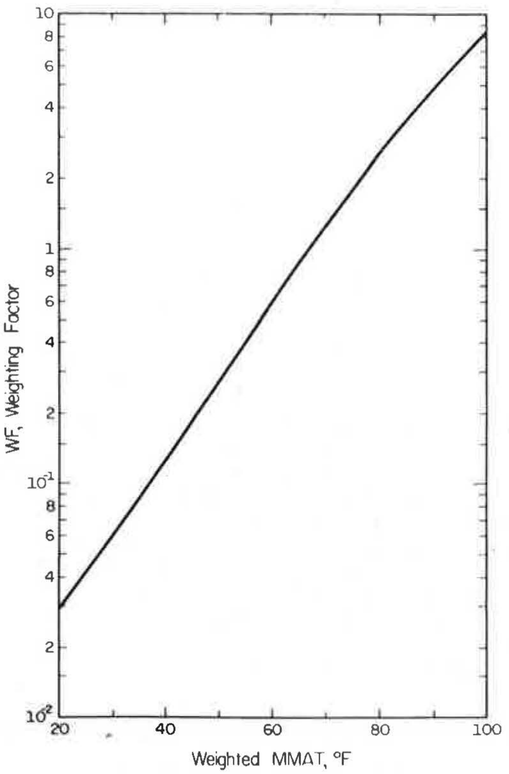


Figure 11. WMMAT versus mixture temperature.

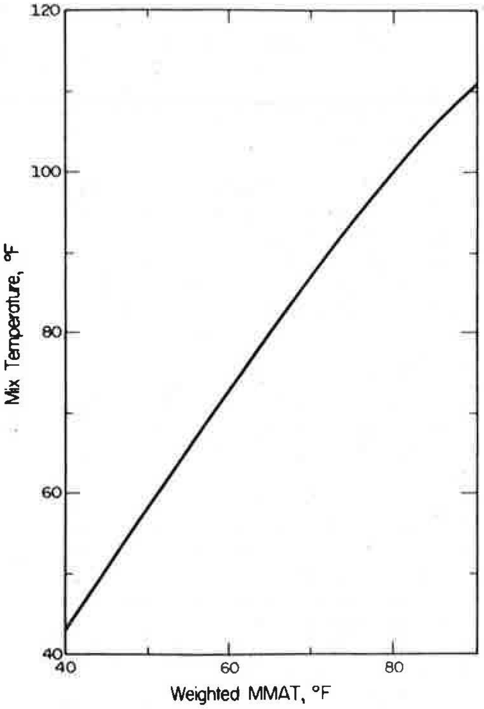
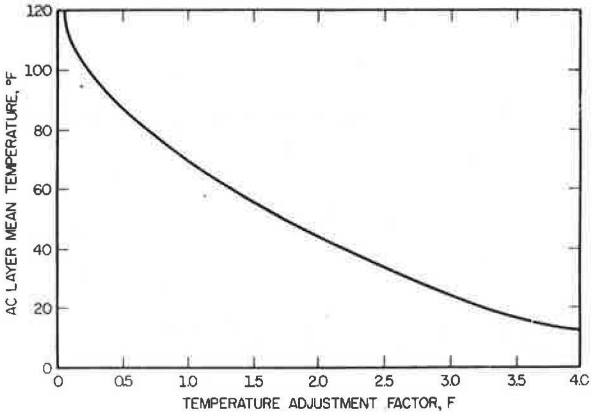


Figure 12. AC temperature adjustment factors (normalized from Figure 6).



than 2 and the existing AC layer is intact (no class 2 cracking), the combined layer thickness is the sum of the existing AC layer thickness plus the overlay thickness and the combined layer modulus is equal to the existing AC modulus. If the modular ratio is greater than 2, the overlay mixture thickness should be adjusted (based on an Odemark transformation concept) to an equivalent thickness of the existing AC:

$$T_{\text{equivalent}} = T_{\text{overlay}}\ [E_{AC}(\text{overlay})/E_{AC}(\text{old mix})]^{3}$$

The combined layer thickness is the sum of the equivalent thickness plus the existing AC thickness, and the combined layer modulus is equal to the existing AC modulus.

5. Adjust the subgrade E_{ri} determined from NDT testing for climatic effects by using the adjustment factors given in Table 1. E_{ri} determined for the summer-fall period is assigned a factor of 1.0 (no adjustment required). To predict spring E_{ri} from summer-fall data, multiply by the appropriate adjustment factor in Table 1. To predict summer-fall E_{ri} from spring data, divide the spring E_{ri} by the appropriate adjustment factor in Table 1.

Table 1. Subgrade climatic adjustment factors.

	Adjustment Factor			
	Well-Drained or Better[a]		Other[a]	
USDA Soil Types	Freeze-Thaw	No Freeze-Thaw	Freeze-Thaw	No Freeze-Thaw
Silt, silt loam, loam, sandy loam	0.70	0.85	0.50	0.60
Silty clay loam, clay loam, sandy clay loam, sandy clay, silty clay, clay	0.65	0.85	0.50	0.75

[a] USDA internal drainage classes.

6. Establish past (if possible) and future traffic. Many agencies have procedures for reducing mixed traffic to equivalent 18-kip single-axle loads (SALs). The present Illinois DOT procedure (9) is being used in initial implementation activities.

Overlay Thickness Requirement

Based on design traffic considerations (18-kip SALs) a design deflection is determined from Figure 7 or 8. By using the ILLI-PAVE-based algorithms in Figure 2 with spring E_{AC} and E_{ri} values, the overlay thickness required to achieve the design deflection value can be determined.

The overlay thickness determined will be conservative because the input values are appropriate for spring conditions. To refine the thickness determination, seasonal effects can be considered by using a Miner-based percentage of life consumption approach. Assume that the total design traffic is uniformly applied (one-twelfth of the traffic is experienced each month).

For the overlay thickness determined for the spring condition, calculate a summer-fall deflection based on summer-fall E_{AC} and E_{ri} inputs. By using the relations between surface deflection and traffic (Figures 7 and 8), the allowable traffic for the spring and summer-fall deflections can be determined.

Calculate the percentage of life consumed by

$$P_i = (N_i/N_{Ti})(100) \tag{4}$$

where

P_i = traffic life consumption for the ith period (%),
N_i = number of 18-kip SALs applied during the ith period (spring or summer-fall), and
N_{Ti} = allowable traffic for seasonal pavement surface deflection of interest (spring or summer-fall).

A refined design is achieved by iterating on overlay thickness until the total percentage of traffic life consumption (spring plus summer-fall deflections) is equal to or less than 100.

Current Illinois DOT practice is to round off the overlay thickness to the nearest 0.25 in., (minimum = 2 in.).

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

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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