Hot-Mix Asphalt Layer Thickness Design for Longer-Life Bituminous Pavements

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The performance of a hot-mix asphalt (HMA) pavement structure is dependent on the interaction between pavement responses and the strength and modulus of the different layers. Wheel loads induce stresses and strains in each layer, which can result in damage of bound and unbound materials. The accumulation of damage within the pavement layers eventually becomes visible at the surface of the pavement in the form of rutting, cracking, and surface roughness. Structural deterioration is normally associated with cracking and rutting. These two distresses, along with the cumulative or incremental damage concept, historically have been used in determining the layer thickness requirements needed to resist structurally related distresses.

An overview is presented of a procedure that has been used to design long-life HMA pavement structures for heavily traveled roadways. The design procedure is based on limiting the tensile strain at the bottom of the HMA layer and the vertical compressive strain at the top of the subgrade or embankment soil. Long life is defined in this paper as 40+ years without any major structural failures throughout the HMA layer. The design traffic used in previous design studies has exceeded 40 million equivalent single-axle loads.

The methodology applies the cumulative damage concept in the prediction of fatigue (load-related cracking) and subgrade distortion. Seasonal and other variations in material properties, including the modulus of the HMA layer, are considered in the procedure by use of the "equivalent modulus" concept. In other words, the incremental damage computed in the HMA layer for a specific modulus would be equal to the summation of the incremental damage computed allowing the modulus of the HMA layer to change with the season. Two other criteria are used for the mechanistic–empirical thickness design checks. One is based on limiting the maximum surface deflection under the design load and the other is based on limiting the modulus ratio between two adjacent unbound pavement layers.

With this methodology, three key issues related to fatigue cracking in HMA layers are addressed. The first issue is the reality of the concept of an "endurance limit" for the layer thickness design of HMA layers. The second issue is the location of where load-related cracks initiate in the HMA layer (at the bottom of the layer versus the top of the layer), and the third issue is confirmation of the fatigue characteristics of HMA layers for use in layer thickness design. Some of the Long-Term Pavement Performance data, both materials and distress data, are used to support the criteria employed in the design procedure and the methodology of that procedure.

A pavement's service life is defined as that period of time from completion (or opening to traffic) until the condition of the pavement is considered unacceptable and rehabilitation or replacement is required. The determination of pavement life is dependent upon the structural design requirements, material characteristics, layer thickness, maintenance activities and failure criteria established by the agency or owner.

For high volume roadways, designing pavements for long service lives is becoming more common in the industry. In fact, the industry is referring to these types of pavements as perpetual designs. Perpetual or long life is defined in this paper as 40+ years without any major structural failures or repairs. In other words, the repair or rehabilitation of these types of pavements is limited to deterioration that initiates at the surface (i.e., a repair strategy of shave and pave or mill and replace the surface layer).

Pavement performance is normally predicted as a function of several factors that can be divided into the following major categories:

1. Traffic loading [normally expressed in terms of 18 kip equivalent single-axle loads (ESALs)];
2. Climatic condition (e.g., precipitation, temperature, and freezing index);
3. Subgrade parameters (e.g., subgrade soil type, resilient modulus, and other physical properties);
4. Pavement parameters (e.g., layer thickness, drainage, and age);
5. Pavement materials (e.g., resilient modulus, strength, and other physical properties); and
6. Maintenance level (e.g., amount of patching, crack sealing).

The performance of a pavement structure is dependent upon the interaction between pavement response and strength of the different layers. Wheel loads induce stresses and strains in each layer, which can result in permanent deformation or damage of pavement materials. The accumulation of permanent deformation and damage of the pavement eventually becomes visible at the surface of the pavement in the form of rutting, cracking, or surface roughness. Since pavement structural deterioration is normally associated with cracking and rutting, these two distresses, along with the accumulative damage concept, have been used in developing the pavement thickness and material combinations needed to prevent structurally related distresses.

The materials and environmental types of surface distress are generally the limiting factors in determining the service life of flexible pavements and hot-mix asphalt (HMA) overlays. Improved material and mixture selection and construction specifications are used to reduce the expected occurrence of the material and environmental related distresses. This paper presents a summary and overview of a design procedure that has been used for designing long-life HMA pavements for traffic levels exceeding 40 million ESALs.

THICKNESS DESIGN METHODOLOGY

The structural deterioration of flexible pavements is associated with cracking in the HMA surface or development of ruts in the wheel path. The methodology applies the cumulative damage concept in the prediction of these two modes of distress. Use of the cumulative damage concept permits accounting, in a rational manner, for damage caused by each load application.

Seasonal and other variations in material properties and modulus of each layer with different loads can be considered in these predictions of damage. Evaluations of design life for candidate pavement structures are based on computing of damage caused by each truck type and load (or an 18-kip ESAL) for different seasons of the year, and then summing the results to obtain the total damage to the pavement structure.

The objective of the design effort is to provide pavement structures that will serve the design traffic levels projected through a design period before experiencing failure. Failure of flexible pavements is defined as alligator cracking over 10 percent of the area subjected to wheel loads or one-half inch of rutting. The failure of a pavement system under this concept is assumed to occur when the damage index reaches a fixed amount, generally 1.0. It should be understood that a damage index of one does not necessarily imply a functional failure, but is instead that level of damage selected as sufficient to warrant maintenance or rehabilitation.

For this study, a damage index of one means the pavement has been subjected to a sufficient number of wheel loads to cause 10 percent alligator cracking or 0.5 inches of rut depth (as defined by the SHRP pavement distress manual) (*1*). These values of 10 percent cracking and 0.5-inch rut depth were selected because previous studies of in-service pavements have indicated that these levels will usually trigger some type of pavement rehabilitation.

Two other criteria were used for the mechanistic–empirical thickness design checks. One is based on limiting the maximum surface deflection and the other is based on limiting the modulus ratio between two adjacent unbound pavement layers. These two criteria and the rutting and fatigue criteria used for the design checks are discussed and defined in the following paragraphs.

STRUCTURAL RESPONSE DESIGN CRITERIA

Limiting Modulus Ratio Criteria for Unbound Aggregate Layers

The long term in place modulus of unbound base and subbase layers are dependent on the modulus of the supporting layer because of potential de-compaction in the lower portion of these layers. The U.S. Army Corps of Engineers developed criteria to limit the modulus of unbound aggregate layers based on the thickness of an unbound aggregate layer and the modulus of the layer supporting the unbound aggregate layer (*2*). These limiting modulus ratio criteria are graphically shown in Figure 1 and were used in determining the maximum layer modulus of unbound aggregate base and subbase layers.

Subgrade-Embankment Protection Criteria

Rutting or surface distortion is considered to occur primarily in the subgrade and has been related to the vertical compressive strain at the top of the subgrade by the following empirical functional form.

$$\log N_{fv} = b_3[\log(M_{R(\text{soil})})] - b_2[\log(\varepsilon_{vs})] - [\beta_v b_1] \quad (1)$$

where

N_{fv} = number of load repetitions for subgrade distortions that cause surface distortions exceeding 0.5 inches in depth,
$M_{R(\text{Soil})}$ = design resilient modulus of the subgrade soil or foundation (psi),
(ε_{vs}) = vertical compressive strain at the top of the subgrade soil or foundation;
b_1, b_2, b_3, = soil properties from repeated load triaxial tests [b_1 is also adjusted to correlate the laboratory test results to field observations ($\beta_v\, b_1 = 10.90$, $b_2 = 4.082$, and $b_3 = 0.955$)], and
β_v = field calibration factor for subgrade distortion–vertical strain.

This assumption implies that the structural layers above the subgrade or foundation will be constructed such that only negligible rutting will occur within those layers. Figure 2 shows the relationship between vertical compressive strain and number of wheel load applications for various subgrade stiffness values that were utilized to approximate a failure level of subgrade rutting or distortion (*2, 3*).

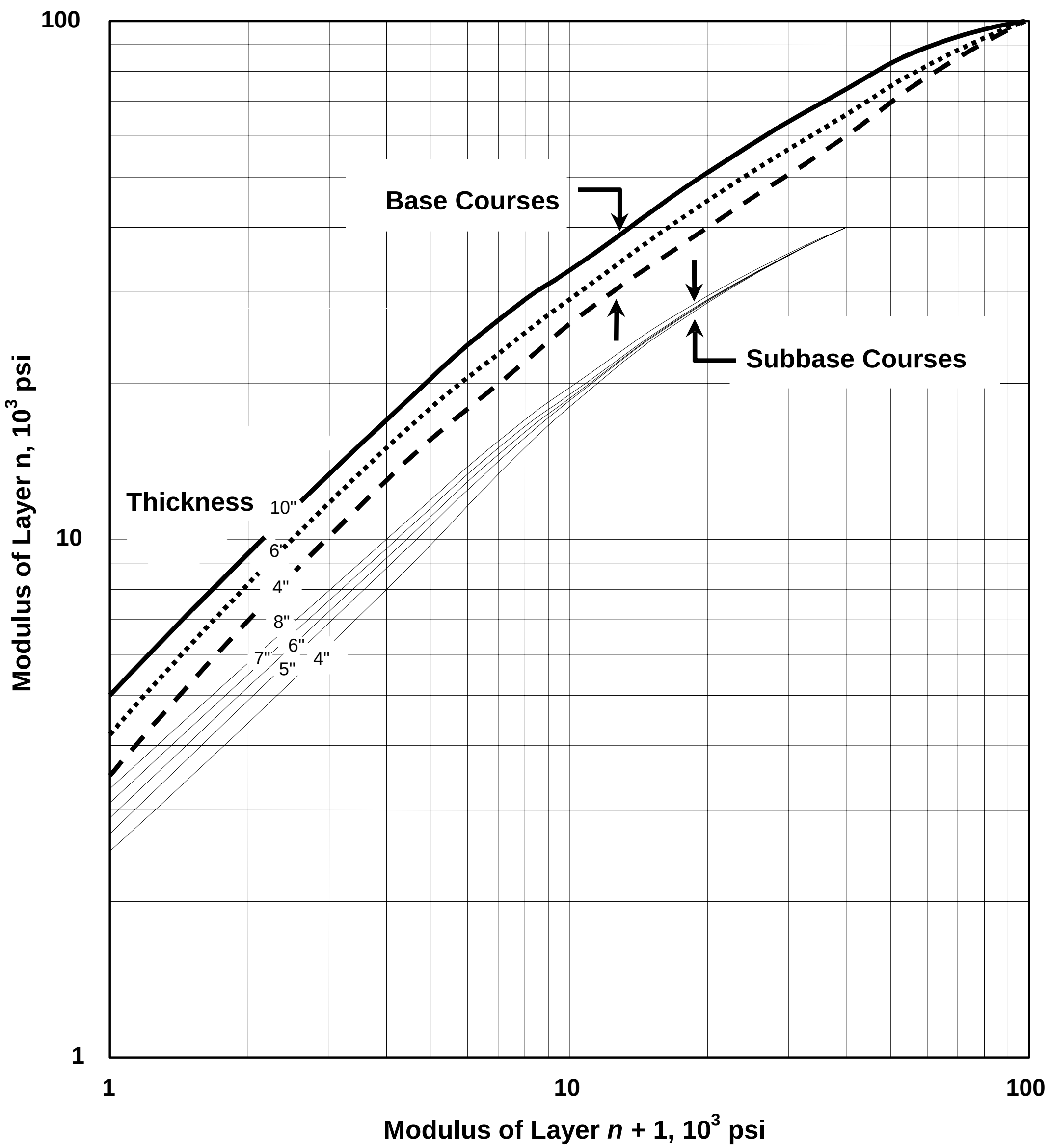

FIGURE 1 Limiting modulus criteria of unbound aggregate base and subbase layers (*2*) (1 in. = 0.0254 m; 10^5 psi = 698 MPa).

The soil properties b_1, b_2, and b_3 are obtained through triaxial repeated load permanent deformation tests in the laboratory. The regression coefficient b_1 is shifted or adjusted to correlate laboratory results to a specific level of subgrade distortion. This assumes that the materials placed above the foundation will be properly compacted and of sufficient strength so that significant permanent deformation will not occur in those layers.

Fatigue Cracking Criteria

Fatigue or alligator cracking in flexible pavements results primarily from repeated wheel loads and has been related to the horizontal tensile strain at the bottom of the HMA layer by the following empirical functional form (*4*).

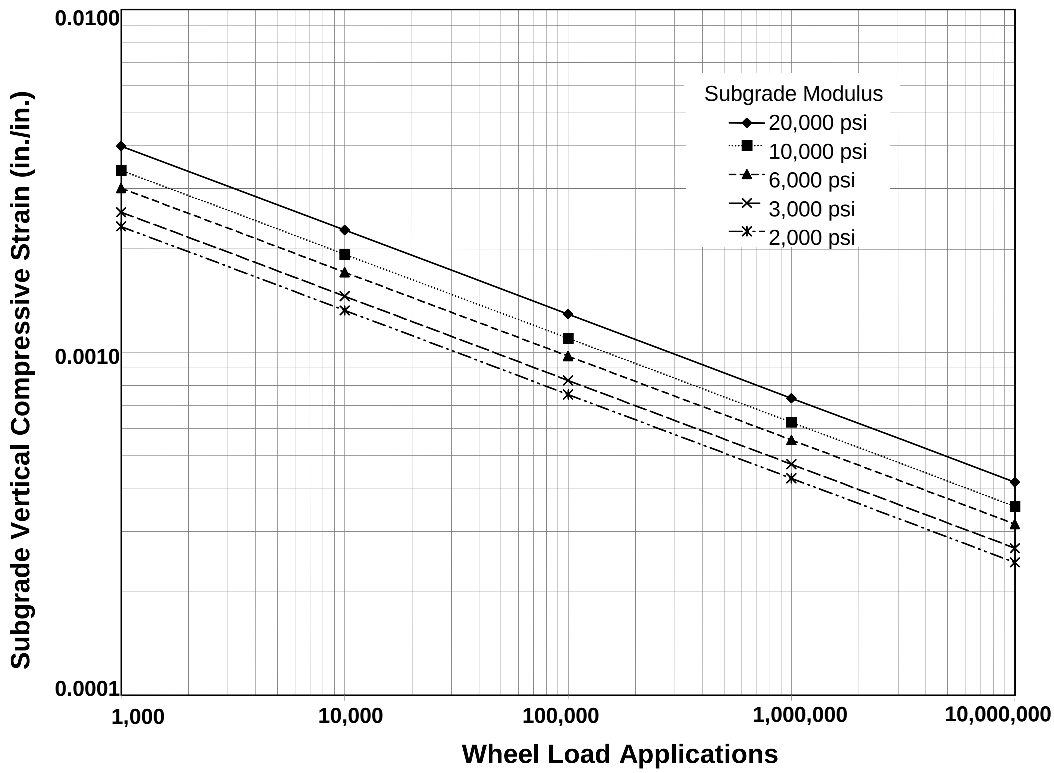

FIGURE 2 Relationship between subgrade vertical compressive strain and wheel load applications for the deformation failure criteria (*2*).

$$\log N_{ft} = \beta_t k_1 - k_2[\log(\varepsilon_t/10^6)] - k_3[\log E/10^3)] \quad (2)$$

where

N_{ft} = number of load repetitions to specific level of fatigue cracking;
ε_t = tensile strain at the bottom of the HMA layer;
E = modulus for the HMA mixture (psi);
k_1, k_2, k_3 = HMA material properties determined from beam fatigue tests ($\beta_t k_1$=14.820 for crack initiation, $\beta_t k_1$=15.947 for less than or equal to 10 percent area cracking, and $\beta_t k_1$=16.086 for more than 45 percent area cracking; k_2=3.291; k_3=0.854); and
β_t = field calibration factor for fatigue cracking–tensile strain.

The material properties k_1, k_2, and k_3 are obtained through fatigue beam testing in the laboratory. The shift factor β_3 is used to correlate laboratory results to actual field behavior at different levels of load-related cracking. The shift factor varies by the failure criteria (i.e., the extent of fatigue cracking) and can be dependent on the HMA mixture composition. Von Quintus and others found that the field calibration factor was highly dependent on the indirect tensile strain at failure and on the total resilient modulus (*5, 6*). Figure 3 shows the relationship used in this study between HMA tensile strain and number of load applications to produce 10 percent alligator cracking for various HMA modulus values, assuming that the load-associated cracks initiated at the bottom of the HMA layer (*4*).

Total fatigue cracking in the field is predicted using the cumulative damage approach. Miner's law is used to accumulate the fatigue cracking damage for the different wheel loads on a seasonal basis over the analysis period using the following relationship:

$$D_k = \sum_{j=1}^{k} \sum_{i=1}^{m} \frac{n_{ij}}{N_{fij}} \tag{3}$$

where

D_k = fatigue damage through season k,
m = number of load classes,
n_{ij} = actual number of load repetitions for load class i ($i = 1,\ldots, m$) during season j, and
N_{fij} = number of load repetitions for load class i and season j to reach failure.

Load-related fatigue cracks also initiate at or near the surface and propagate downward. This type of fatigue cracking is believed to occur more commonly on pavements with thick HMA surface layers where large stiffness or modulus gradients exist. Surface-initiated fatigue cracks generally start as longitudinal cracks near the edge of the wheels. The mechanisms that cause these types of cracks to develop at the surface are believed to be a combination of the tensile and shear modes adjacent to the wheel loads and are discussed in a later section of this paper. Extensive validation of the mechanisms has yet to be finalized.

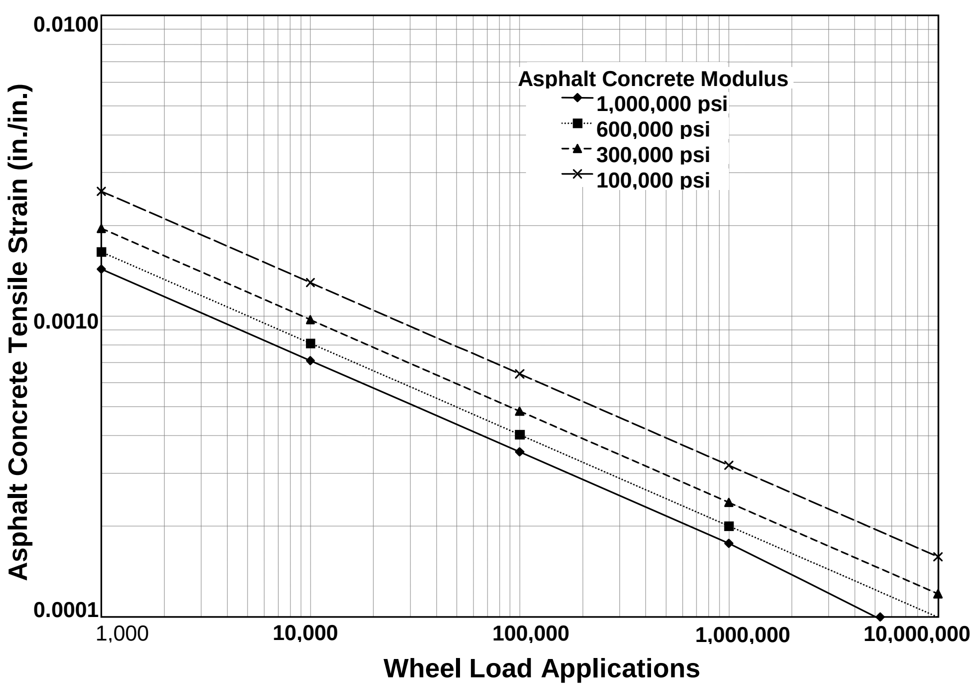

FIGURE 3 Relationship between asphalt concrete tensile strain and wheel load applications for the alligator cracking failure criteria (*4*).

Maximum Surface Deflection Criteria—Overall Structural Adequacy Check

The maximum surface deflection under a 9-kip gear load or 18-kip axle load has been used for pavement design and evaluation. Various design criteria have been developed by different agencies, but the critical deflection relationships defined from the AASHO Road Test or Transport Research Laboratory are the ones most commonly used (*7, 8*). The critical deflections are used to judge the acceptability of the pavement design cross section and not to predict the occurrence of specific distresses.

MATERIALS RESPONSE CRITERIA

Permanent Deformation

Although the subgrade protection criteria assumes that no permanent deformation will occur within the pavement layers, surface distortions or rutting may be the consequence of permanent deformation (or plastic strains) within HMA layers, unbound aggregate layers, or both. The design methodology for long life HMA pavement should consider both contributions to rutting. The empirical permanent deformation model for both bound and unbound materials is a power law function of the following form.

$$\frac{\varepsilon_p}{\varepsilon_r} = \beta_i a N_b \qquad (4)$$

where

ε_p = accumulated plastic strain in layer h_i after N load repetitions,
ε_r = resilient strain at the mid-depth of layer h_i,
N = number of load repetitions,
a, b = material properties, and
β_i = field calibration factor for permanent deformation in the pavement layers.

To calculate total pavement rutting, the pavement resilient strains are estimated at representative locations (e.g., midthickness of layers/sublayers). The rut depths for each layer are estimated for different wheel loads on a seasonal basis over the analysis period using the following relationship (*6*).

$$RD = \Sigma[\varepsilon_{pi}(N)h_i] \qquad (5)$$

where

RD = total rut depth for the pavement layers and subgrade (inches),
$\varepsilon_{pi}(N)$ = accumulated plastic strain at N load repetitions for layer i, and
h_i = thickness of layer i (inches).

Thermal Cracking

The thermal cracking model is based on the original work done by Roque and Hiltunen during the SHRP program (*9*). This model was subsequently enhanced as part of the on-going work under NCHRP Project 9-19 (Superpave Support and Performance Models Management). The thermal cracking predictive model is founded on mechanics, specifically fracture mechanics, rather than on empirical relationships between laboratory-field performance and various predictor variables. The extent of cracking in the field is predicted from the model using an assumed relationship between a probability distribution for crack length and the percent of cracking:

$$\begin{aligned} C_f &= \beta_5 * \text{Prob}(\log C > \log h_{AC}) \\ &= \beta_5 * \text{N}\left(\frac{\log\left(C / h_{AC}\right)}{s_{\log a}}\right) \end{aligned} \tag{6}$$

where

C_f = observed amount of thermal cracking (expressed as the length of thermal transverse cracks occurring in a pavement length of 500 ft.),
β_5 = field calibration coefficient,
Prob( ) = probability,
C = predicted crack depth (from the Roque-Hiltunen mechanistic thermal cracking model),
h_{AC} = thickness of the asphalt layer,
N( ) = standard normal distribution, and
$s_{\log a}$ = standard deviation of the log of crack lengths in the pavement.

This thermal cracking model was calibrated on a combined set of 22 original SHRP thermal cracking sections, plus 14 C-SHRP and 5 MnRoad sections under NCHRP Project 1-37A (Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures).

DETERMINATION OF DESIGN LAYER MODULUS— EQUIVALENT DAMAGE CONCEPT

Most pavement designs are completed well in advance of the actual selection and use of specific materials and mixtures. When the actual materials and mixtures are unavailable for the structural design process, determination and use of the design layer modulus based on the equivalent damage concept is used instead of breaking a typical year into different seasons and calculating damage for each season and wheel load. In other words, determination is made of an equivalent layer modulus for the entire year that will result in the same total damage when calculating and summing the damage for each season of the year. The following provides an overview of determining the equivalent or design layer modulus for bound and unbound materials.

HMA Materials—Equivalent Temperature Concept

The equivalent annual modulus or the design modulus for HMA mixtures can be determined in accordance with the following equation when using the fatigue relationship of Equation 2 (*3, 7, 10*).

$$E_{design} = [\Sigma E(T)_i \times DF_i]/(\Sigma DF_i) \quad (7)$$

where

$$DF_i = 7.4754 \times 10^{10}[E(T)_i]^{-1.908} \quad (8)$$

E_{design} = The equivalent or annual design modulus for the HMA mixture (psi),
$E(T)_i$ = The HMA modulus for the average middepth pavement temperature (°F) for season i (measured in the laboratory or backcalculated from deflection basins and adjusted to laboratory conditions) (psi), and
DF_i = Fatigue cracking damage factor in season i.

Unbound Materials—Equivalent Seasonal Modulus

Damage factors for unbound aggregate base and subbase layers (based on fatigue cracking of the HMA layers) can be used to ensure that there is sufficient cover or surface thickness to prevent overstressing the base and subbase materials and inducing high tensile strains in the HMA surface layers during periods of increased moisture. The equivalent annual aggregate base or subbase modulus can be determined in accordance with Equation 9 (*10*).

$$M_{R(\text{Aggregate})} = \Sigma[(M_{RA})_i \times (UF)_i]/[\Sigma(UF)_i] \quad (9)$$

where

$$(UF)_i = 1.885 \times 10^3(M_{RA})_i^{-0.721} \quad (10)$$

$M_{R(\text{Aggregate})}$ = the equivalent annual resilient modulus for unbound aggregate base and subbase materials (psi),
$(UF)_i$ = damage factor for unbound aggregate base and subbase materials in season i, and
$(M_{RA})_i$ = resilient modulus of the unbound aggregate base or subbase measured in the laboratory for a moisture content in season i (psi).

Permanent deformation damage factors (based on distortion in the subgrade) are used to ensure that there is sufficient cover to prevent overstressing and excessive permanent deformation in the subgrade during periods of increased moisture. The following equations can be used to calculate an equivalent annual or design resilient modulus for the subgrade soil (*10, 11*).

$$M_{R(\text{Soil})} = \Sigma[(M_{RS})_i(US)_i]/\Sigma(US)_i \quad (11)$$

$$(US)_i = 4.022 \times 10^7(M_{RS})_i^{-1.962} \quad (12)$$

where

$M_{R(\text{Soil})}$ = equivalent or design resilient modulus of the subgrade soil (psi),
$(M_{RS})_i$ = resilient modulus for the subgrade soil measured in the laboratory for a moisture content or physical condition within season *i* (psi), and
$(US)_i$ = damage factor for the subgrade soil in season *i*.

Backcalculated Versus Laboratory-Determined Layer Modulus

The design modulus for each layer within the pavement structure represents the modulus of that layer determined from laboratory tests. If the layer modulus is backcalculated from deflection basin data, the layer modulus is reduced according to the types of materials in accordance with the procedure established by Von Quintus et al. (*3, 12*). The reason for reducing the backcalculated layer modulus is that the structural response and calibration factors were based on laboratory-measured modulus, rather than on backcalculated elastic layer modulus.

KEY DESIGN ISSUES

This section of the paper identifies and briefly discusses some of the key issues related to the design of long-life HMA pavements. These issues are three—the applicability of an endurance limit for HMA mixtures, the applicability of the criteria for surface initiated fatigue cracks, and site factors and conditions affecting design.

Endurance Limit for HMA Mixtures

The concept of an endurance limit is used in other disciplines but has not been accepted or used for designing HMA pavements. The endurance or fatigue limit is defined as the horizontal asymptote of the relationship between the applied stress or strain and the number of load repetitions, such that a lower stress or strain will result in an infinite number of load repetitions.

For long-life HMA pavements, the applicability of an endurance or fatigue limit has become a key issue in determining the HMA layer thickness requirements. With the fatigue equations that have been developed over the years, the greater the design traffic, the thicker the pavement. Whether HMA has an endurance limit as a material/mixture property is debatable. However, there is a limit for which the allowable number of load applications become so large that laboratory beam fatigue tests confirming the fatigue strength of the mixture become impractical. This value seems more of a “practical” limit than an endurance limit.

There have been only a few studies or papers suggesting values for the endurance limit. Most values used or suggested are tensile strains less than 0.000100 in./in. The author has used a value of 0.000065 in./in. at the equivalent annual pavement temperature for this “practical” limit for HMA layers. This value was obtained from a limited amount of data based on a limiting strain ratio rather than a specific value, and it is believed to be more realistic. The strain ratio is defined as the initial tensile strain applied to the HMA layer divided by the tensile strain at failure, as measured from the indirect tensile test. Figure 4 shows the relationship between the indirect tensile strain at failure and total resilient modulus (*6*). In a few limited studies, HMA mixtures were found to have no area fatigue cracks when the ratio is less than 10 percent (*13*). This criterion has been used for determining the HMA layer thickness required for long-life pavements but should be confirmed through extensive laboratory and field studies.

Surface-Initiated Fatigue Cracks

Most load related fatigue analyses for determining the HMA layer thickness assume that the cracks initiate at the bottom of the HMA layer and propagate upward to the surface of the pavement. For thick HMA layers, however, there is more and more evidence and studies that suggest these load-related cracks can actually initiate at the surface and propagate downward. There are various opinions on the mechanisms that cause these types of cracks, but there is no conclusive data to suggest one is more applicable than the others. Some of the more common opinions are:

- Tearing of the HMA surface mixture from radial tires with high contact pressures near the edge of the tire causes the cracks to initiate and propagate in shear and in tension.
- Severe aging of the HMA mixture near the surface (large modulus gradient) resulting in high stiffness that, when combined with high contact pressures adjacent to the tire loads, causes the cracks to initiate and propagate in shear. And
- A combination of thermal strains and stresses and of tensile strains near the surface and adjacent to the tire loads causes the cracks to initiate and propagate in tension, a process accelerated by the aging of the HMA mixtures near the surface.

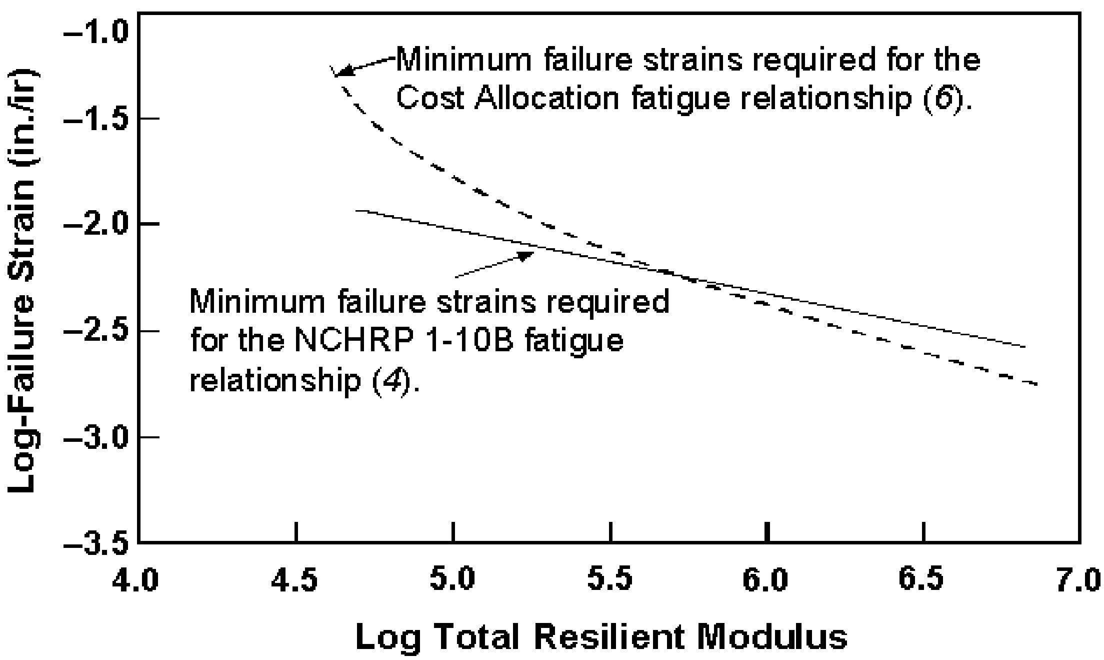

FIGURE 4 Relationship between the failure strain and total resilient modulus as measured using the indirect tensile test (*6*).

Site Factors and Conditions Affecting Design

Climate

One of the important although complex factors that affect pavement performance is the climate. This is especially true in those areas of the United States that experience large variations in temperature and moisture. Air temperatures and other climatic parameters are used to calculate the temperature throughout the pavement structure to determine the HMA modulus and pavement response characteristics. Temperatures are especially important in predicting the level of transverse cracking for a particular HMA mixture.

Moisture can also be important in determining the modulus of unbound pavement materials and soils, but is extremely difficult to predict. However, moisture has an important effect on the resilient modulus of the unbound materials and soils. Historical data should be used to determine the seasonal or monthly variations in the underlying unbound layers and supporting soils.

Subsurface and Drainage Investigations

It is critical that adequate subsurface investigations be performed for both new and rehabilitated HMA pavements to identify response characteristics of the supporting soils and subsurface water flow that can have a detrimental impact on the long-term performance of the pavement. Adequate drainage layers should be designed to prevent ground water or subsurface water flow from infiltrating and significantly reducing the strength of the unbound pavement materials and soils (*14*).

Subgrade Soil

The properties of the roadbed soil are essential inputs in the pavement design process. Methods characterizing soil properties include strength, resilient modulus, shrink-swell potential and frost susceptibility, as well as other types of properties. It is suggested that the unbound pavement layer supporting the HMA mixtures have a minimum equivalent modulus of 25,000 psi. Moderate to high frost-susceptible soils (as classified using the Army Corps of Engineers procedure) should be protected from frost penetration and freeze-thaw weakening. Expansive soils can be very destructive to the service life of all pavements, but this is difficult if not impossible to simulate this in design studies. When expansive soils are encountered along the project site, special precautions should be made to eliminate or significantly reduce the effect of differential volume change in the supporting soils.

SUMMARY

The methodology presented in this paper is believed to represent the state of the art in pavement design for long-life HMA pavements. Although the methodology offers capabilities unavailable through more conventional procedures and should be considered more accurate, its predictions of damage and/or distress may be claimed to be as good as the state of the art allows only if the traffic forecast (both in magnitude, axle weight, and tire pressures) is reasonably accurate. The point of this discussion is that these damage predictions offer valuable information for planning and design purposes, but that they are approximate, as are most engineering analyses involving soils and pavement materials.

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