Overview of a Rational Asphalt Concrete Mixture Design for Texas

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A rational asphalt concrete (AC) mix design and analysis methodology was developed. The term "rational" meant that the material properties evaluated in the mixture design and analysis could be used with a layered-elastic pavement model and mechanistic-empirical formulations that relate to pavement performance. The procedures proposed in this study were intended to be used in conjunction with the current Texas State Department of Highway and Public Transportation method of mix design in a complementary fashion. Three major modes of pavement distress—(a) rutting, (b) flexural fatigue, and (c) low-temperature cracking—were addressed. In addition to mixture properties, structural arrangement of pavement layers and environmental factors have significant effects on the performance of AC mixtures. Therefore, a comprehensive mix design should not be performed independent of pavement structural design. Asphalt mix design and pavement structural design parameters were brought together in an integrated fashion.

Hot-mix asphalt (HMA) mix design has long been a trial-and-error process. Two major empirical methods of mix design have emerged as those most commonly used by the asphalt community. The Hveem (ASTM D1560) and Marshall (ASTM D1559) methods have evolved over the past four decades. They are both regarded as empirical methods. There are many variations of these basic methods (see Figure 1) in use among state highway agencies (*1*). Texas State Department of Highways and Public Transportation (SDHPT) has its own unique method of mix design, which is basically a modified Hveem procedure (*2*).

According to the Asphalt Institute (*3*), all mix design procedures must provide the following:

1. Sufficient asphalt to ensure a durable pavement;
2. Sufficient mixture stability to satisfy the demands of traffic without distortion or displacement;
3. Sufficient voids in the final compacted mix to allow for a slight amount of additional compaction due to traffic loading; sufficient voids for expansion of asphaltic cement without flushing, bleeding, and loss of stability; and low enough voids to keep out harmful air and moisture; and
4. Sufficient workability to permit efficient placement of the mix without segregation or shoving.

Historically, the Hveem and Marshall methods have served well; however, they are often used beyond their originally intended realm of empiricism. That is precisely why these methods have proven to be inadequate in addressing today's in-service performance problems. Such problems are associated with variations in the crude source and refining processes, use of additives and modifiers (*4*), type of mix (e.g., large-stone or open-graded) (*5*), and current trends toward heavier traffic loads and higher tire pressures (*6*).

Serious shortcomings of current methods of mix design have led researchers to search for mix design methods on the basis of mechanistic parameters. Recently, a study was funded by Texas SDHPT with the objective of developing a rational mix design and analysis procedure to address different modes of pavement distress in terms of HMA mechanistic parameters.

TEXAS MIX DESIGN METHODOLOGY

In Texas' present method of mix design (*2*), the basic philosophy is to produce a mix with adequate Hveem stability and a target air voids of 3 percent. The latter, which represents the void content in the pavement after its second summer in service, also requires that the aggregate have adequate polish resistance and a minimum of crushed surfaces.

The Texas gyratory-shear method of compaction is used in specimen fabrication. This method closely simulates the kneading action of roller compactors and further densification caused by traffic. As part of a study called "Asphalt Aggregate Mixture Analysis System (AAMAS)," sponsored by NCHRP, researchers (*7*) noted that the Texas gyratory-shear compactor was better at producing the densification and material properties similar to those developed through field compaction than the processes of the Marshall method.

RESEARCH APPROACH

The philosophy behind this improved mix design procedure is to design an HMA that will provide an adequate level of stiffness to protect the vulnerable subgrade by proper distribution of vertical compressive stresses. There is a tradeoff between the stiffness of HMA and its flexibility. An adequate level of flexibility must be demonstrated by the HMA for it to resist a load-induced, flexural fatigue mode of distress. Once the stiffness and flexibility properties are determined to be acceptable, the permanent deformation potential of HMA can be assessed by means of a constant-stress creep analysis.

Finally, the low-temperature fracture potential is evaluated on the basis of the HMA's stiffness and tensile strength. The temperature susceptibility of the HMA stiffness is characterized by variation of the diametral resilient modulus induced by changes in temperature. The HMA tensile strength is also

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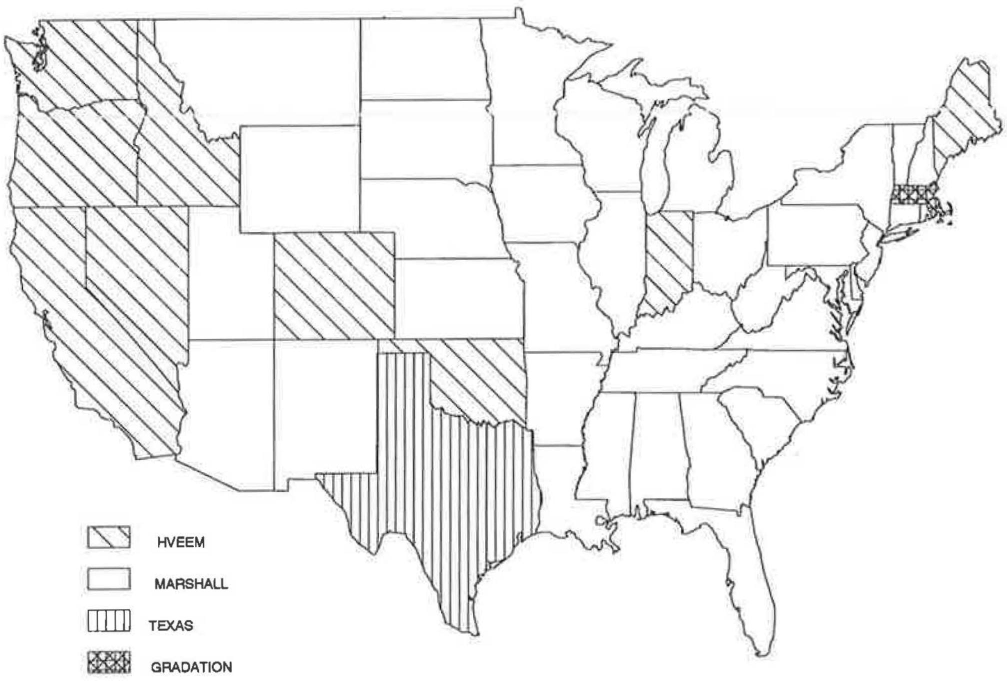


FIGURE 1 Distribution of mixture design methods common in the United States (*1*).

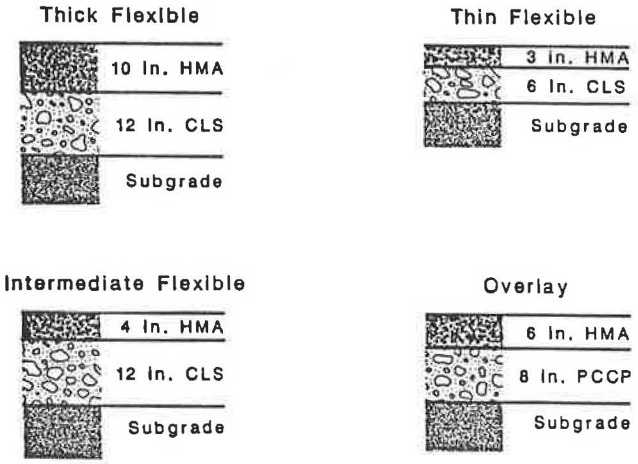


FIGURE 2 Four distinct pavement structural categories.

evaluated diametrally, over a range of temperatures and at a slow rate of loading to simulate the slow thermal contraction and fracture process in the pavement.

The most important aspect of this improved mixture design approach lies in its direct link to pavement structural design. The rationale is that the material properties that determine the success or failure of a pavement structure cannot be adequately assessed without full consideration of the pavement structural conditions.

A system of pavement structural categories was arranged to identify four distinctive categories of pavement structure commonly encountered in the field. The four pavement structures listed in the following paragraph represent the pavement types used in the development of mixture acceptance criteria. Therefore, asphalt mixtures can be evaluated on the basis of mechanical conditions present under a selected set of pavement structural arrangements.

The structural categories and their representative pavement cross sections (Figure 2) were as follows:

- Thick flexible pavement: 10-in. HMA, 12-in. crushed limestone base (CLS), and subgrade (weak, moderate, or soft).
- Thin flexible pavement: 3-in. HMA, 6-in. CLS, and subgrade (weak, moderate, or soft).
- Intermediate flexible pavement: 4-in. HMA, 6-in. CLS, and subgrade (weak, moderate, or soft).
- HMA overlaying a portland cement concrete pavement (HMA/PCCP): 6-in. AC, 8-in. PCCP, and subgrade (weak, moderate, soft).

OVERVIEW OF METHODOLOGY

The methodology is based on a series of mechanistic material characterization procedures that relate directly to the pavement distress modes. The hierarchy of this design and analysis approach may be expressed as the following:

1. Mixture design in accordance with a standard procedure (e.g., Texas method);
2. Mixture stiffness characterization related to threshold resilient modulus for subgrade protection and stiffness and flexibility analysis for flexural fatigue evaluation;
3. Permanent deformation potential analysis; and
4. Thermal cracking analysis.

An overview of this mechanistic methodology is presented in the following sections.

Stiffness Characterization

In flexible pavements, the HMA is normally the stiffest layer and thus the layer that contributes most effectively to distribution of vertical compressive stresses. A high level of subgrade protection can be achieved through the use of a stiff HMA layer. However, a life cycle cost penalty is associated with this simplistic approach; that is, the stiffest HMA layer may not be desirable from a flexural fatigue point of view. The tradeoff situation that exists between subgrade rutting and fatigue cracking will be discussed in the following sections.

Subgrade Rutting

Flexible pavements are usually designed with the stiffest and highest-quality material on the top layer, and with a gradual transition to softer and lower-quality material in the layers below. A methodology was developed for selecting the proper level of HMA stiffness (the HMA threshold resilient modulus) to protect the subgrade from excessive rutting. The criterion was based on earlier work (*8*) synthesized by Monismith and Finn:

$$N_{18} = (6.15 \times 10^{-7})\, \varepsilon_3^{-4} \tag{1}$$

where

N_{18} = number of 18-kip axle passes to cause a ¾-in. subgrade deformation, and
ε_3 = vertical compressive strain (in./in.) at the top of the subgrade.

There are other subgrade rutting models similar to this criterion (Figure 3). All of these models are empirical; however, they are performance based, and input parameters are mechanistic. Therefore, the approach may be regarded as mechanistic-empirical. Figure 4 shows a schematic representation of a subgrade protection criteria chart. A flow chart illustration of the subgrade protection criterion is shown in Figure 5.

Flexural Fatigue

Once a minimum level of HMA stiffness is determined through the subgrade protection criterion, the fatigue resistance of the mixture is analyzed to ensure a proper balance between stiffness and flexibility. The term "fatigue life" is defined as the magnitude of traffic, expressed in terms of the number of 18-kip equivalent single-axle loads (ESALs), that a pavement structure can handle before a certain amount of distress, usually defined as a percentage of cracking in the wheel path area, is observed.

Finn et al. (*9*) developed a fatigue model on the basis of laboratory and field data from the AASHO Road Test (*10*) to predict up to 10 percent cracking in the wheel path area.

$$\log N_f = 15.947 - 3.291 \log(\varepsilon_t) - 0.845 \log\left(\frac{E^*}{10^3}\right) \tag{2}$$

where

N_f = number of cycles (18-kip ESALs) to failure,
ε_t = repeated tensile strain (in./in. $\times 10^{-6}$), and
E^* = complex modulus (psi) of HMA, approximated by the resilient modulus.

Monismith et al. (*11*) stated that stiffness moduli determined from the ratio of applied stress and the recoverable strain (commonly known as the resilient modulus) should provide essentially the same moduli as that determined from creep and sinusoidal loading (commonly known as the com-

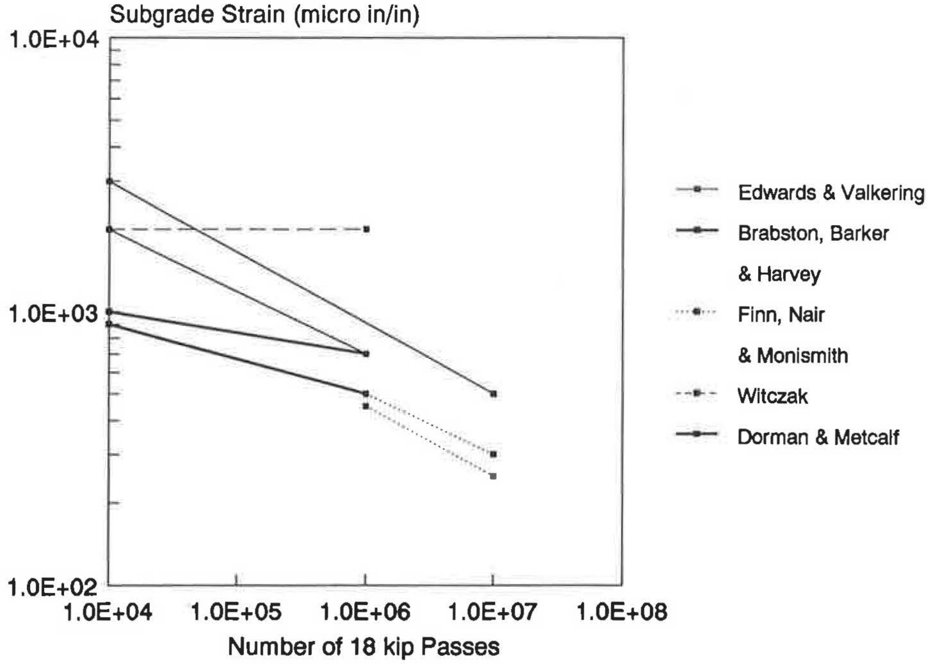


FIGURE 3 Excessive subgrade deformation criteria (*8*).

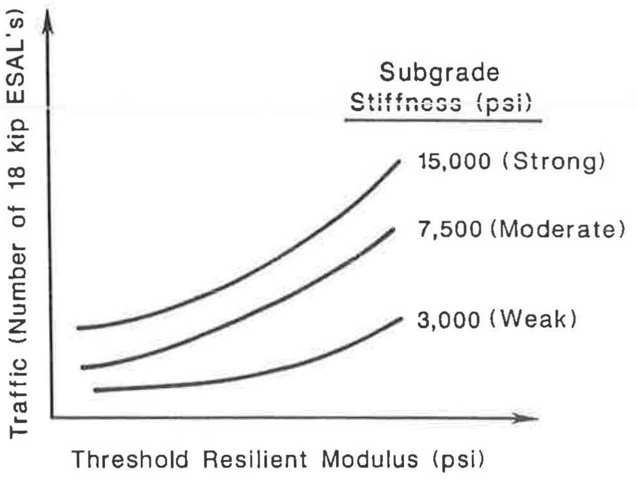


FIGURE 4 Schematic of the threshold resilient modulus of asphalt layer determined on the basis of subgrade excessive deformation criteria.

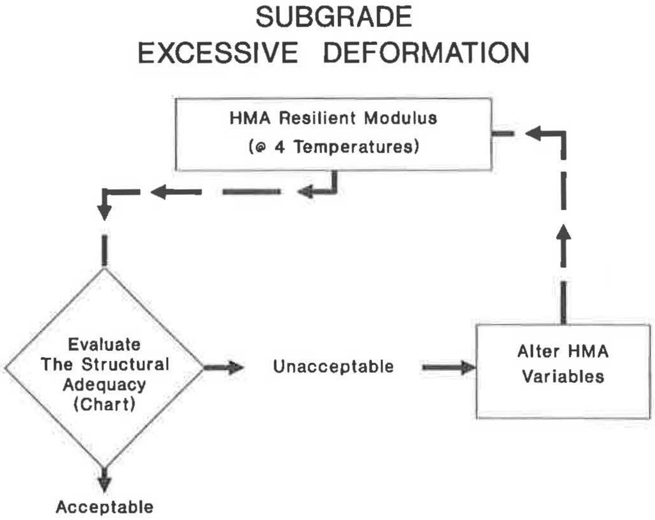


FIGURE 5 Flow chart describing subgrade rutting analysis subsystem.

plex modulus). Hence, the substitution of resilient modulus for complex modulus in Equation 2 is assumed to be valid.

Equation 2 was obtained through laboratory testing followed by shifting of the laboratory data to match the AASHO Road Test (*10*) observations. The resulting shift was about 1,300 percent, which suggests that the actual fatigue life of the pavement in the field was approximately 13 times greater than the laboratory-based predictions. The following explanations could explain this interesting phenomenon:

- Rest periods between traffic loadings, viscoelastic relaxation, and chemical rebonding and healing of asphalt;
- Kneading and surface-crack closing actions of tires; or
- Buildup of residual compressive stresses.

The first step in this rational fatigue analysis approach calls for the evaluation of HMA stiffness at the mean annual pavement temperature (Figure 6). On the basis of this selected value of HMA stiffness, measured in terms of resilient modulus, the induced tensile strain at the underside of the HMA layer is evaluated. Repeated load-induced tensile strain, the primary cause of fatigue cracking, is evaluated from a series of charts developed for each category of pavement structure (Figure 7a). These charts used the results of over 100 computer runs of layered-elastic pavement. The final step in fatigue life evaluation is shown schematically in Figure 7b, which was developed from solutions of layered-elastic pavement runs and Equation 2. Figure 8 is a flow chart representation of the fatigue analysis procedure.

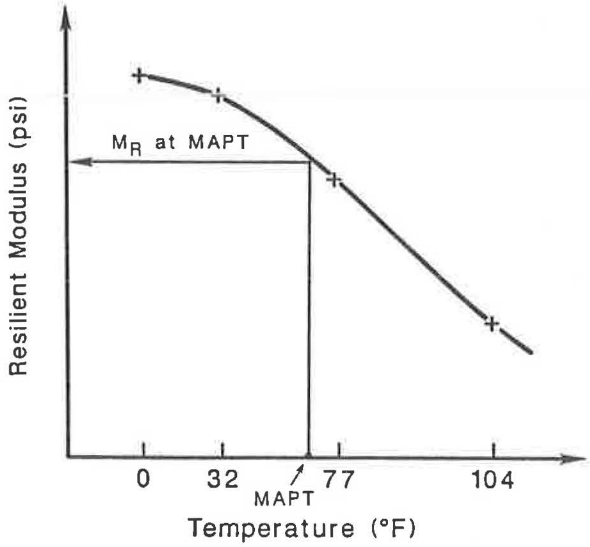


FIGURE 6 Determination of the resilient modulus at the mean annual pavement temperature.

Permanent Deformation

The proposed methodology calls for a static creep-recovery test for evaluation of resistance to permanent deformation potential. The data from this simple test are collected in terms of deformations, both recoverable and irrecoverable, as a function of time. The irrecoverable portion of deformation is responsible for rutting.

A rutting model using the information obtained from the creep-recovery test was developed. This model was based on some earlier work on creep and rutting by Shell researchers (*12,13*). The original Shell rutting model assumes that a linear-elastic relationship (Hooke's Law) is capable of characterizing deformation processes that are by nature not only inelastic but are also viscoelastic, viscoplastic, and plastic. Because of this serious invalid assumption (i.e., using Hooke's Law for characterization of permanent deformation), Shell researchers had to incorporate a composite correction factor into their model.

The relationship between stress level and permanent deformation is not linear (*14–18*). These observations led to the development of a refined version of the original Shell equation. The modified version of the Shell rutting equation does not depend on empirical correction factors; it accounts for

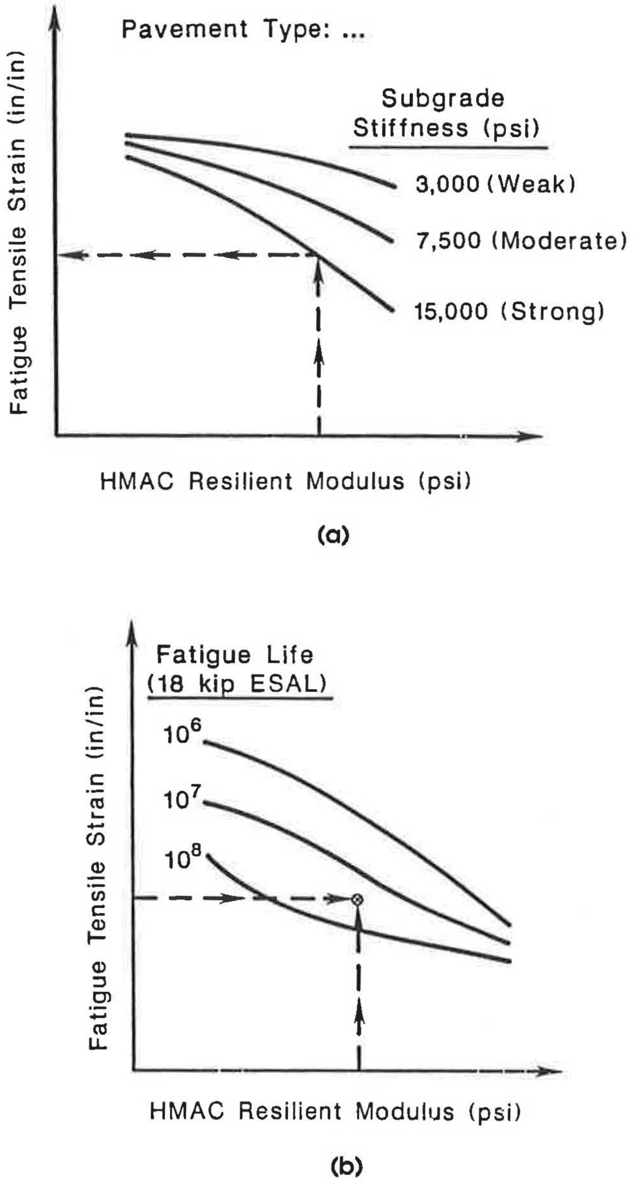


FIGURE 7 **Schematic diagrams representing a, the evaluation of fatigue tensile strain, and b, fatigue life.**

plasticity trends and nonlinearity of such deformations in the following format:

$$h = H\left(\frac{Z\sigma_{\text{tire}}}{\sigma_{\text{lab}}}\right)^{1.61} \varepsilon_{\text{vp}}(t) \qquad (3)$$

where

h = calculated rut depth (in.),
H = asphaltic layer thickness (in.),
Z = vertical stress distribution factor derived from layered-elastic solutions (*13*),
σ_{tire} = average tire contact pressure (psi),
σ_{lab} = stress level (psi) at which the creep test is conducted in the laboratory, and
$\varepsilon_{\text{vp}}(t)$ = viscoplastic trend (in./in.) of the mixture measured by the creep test.

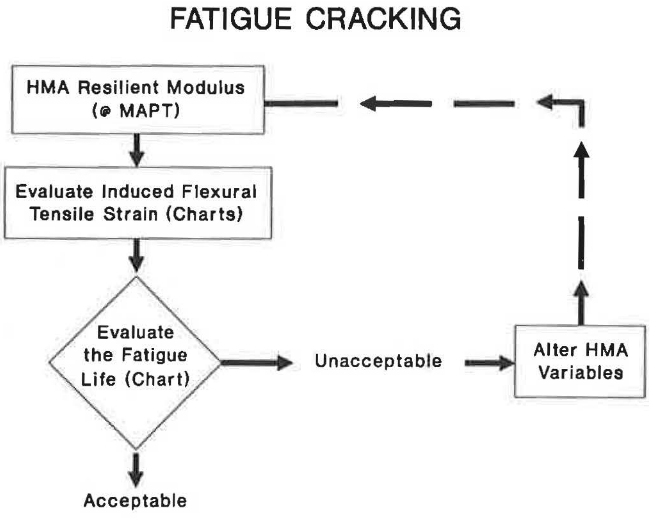


FIGURE 8 **Flow chart describing fatigue analysis subsystem.**

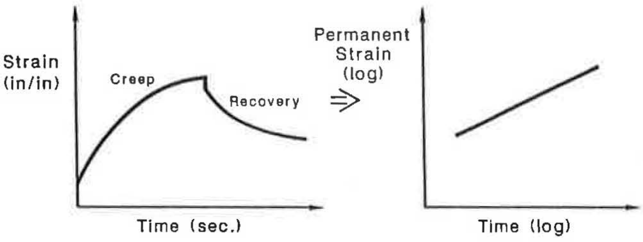


FIGURE 9 **Schematic diagrams describing procedures for characterization of permanent deformation.**

In Equation 3, the ratio of field to laboratory compressive stresses is raised to the exponent 1.61 to account for deformation processes that are nonlinear (i.e., doubling of stress level will triple the rutting). The magnitude of this exponent was determined from several high- and low-stress creep tests and other sources (*14,15,18*).

Rutting criteria charts were developed on the basis of this new rutting model and a stiffness parameter called the "viscoplastic stiffness." The new stiffness parameter is a stress-normalized viscoplastic strain function. Figure 9 shows schematically the procedure by which nonrecoverable strains are characterized as a function of time. Similar to creep stiffness, viscoplastic stiffness has a power-law decay exponent, measured by many researchers (*15,17,18*) to be in the range of −0.25 to −0.27. A set of rutting severity limits (*19*) and assumed power-law–type rutting accumulation rates of 0.25 to 0.27 (the sign change is due to the inverse relationship between strain and stiffness) were the basis for developing a set of rutting criteria charts for specific pavement categories, and layer moduli. Figure 10 shows a schematic of a rutting criteria chart. A flow chart representation of the rutting analysis procedure is shown in Figure 11.

Thermal Cracking

This mode of distress occurs as the result of thermally induced tensile stresses developing in pavement layers. Most methods

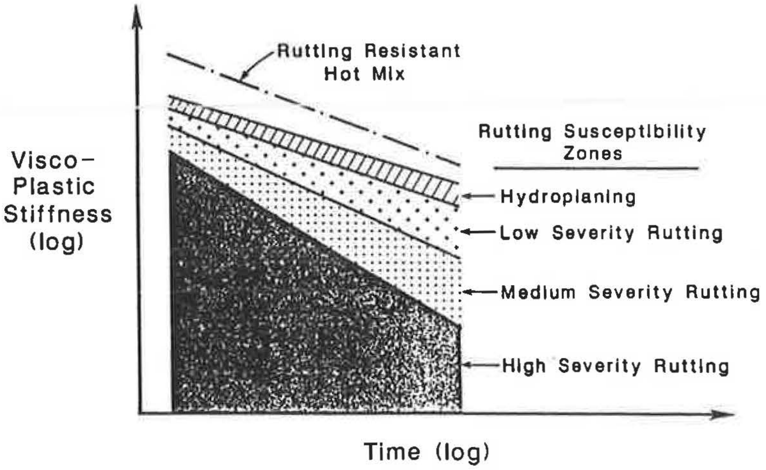


FIGURE 10 Schematic rutting criteria chart.

for calculation of thermally induced stresses are based on algorithms similar to those used in the computer program COLD (*20*). This program was originally developed by Christison (*21*) at the University of Alberta. On the basis of thermal properties of the pavement, solar radiation, and air temperature, the program COLD generates a series of temperature profiles through a one-dimensional finite element routine.

The temperature drop with time induces thermal stresses that could potentially exceed the tensile strength of HMA and induce cracking. Induced tensile stresses are calculated as follows:

$$\sigma_x(t) = \int_{t_0}^{t_1} S(\Delta t,T)\cdot\alpha\cdot dT(t) \qquad (4)$$

where

t = time;
T = temperature;
$\sigma_x(t)$ = induced thermal stress;
$S(\Delta t,T)$ = mix stiffness, time- and temperature-dependent;
$\Delta t = t_1 - t_0$; and
α = coefficient of thermal expansion.

The current version of the COLD program characterizes the HMA stiffness in terms of resilient modulus input over a range of temperatures. On the basis of the relationship between resilient modulus and temperature, the HMA is classified as being within a certain response zone (Figure 12). The response zones were established using an extensive body of existing resilient moduli versus temperature (*22*). Thermally induced stresses are then calculated on the basis of the resilient modulus response zone classification and climatic conditions (e.g., temperature drop rate or solar radiation). These induced conditions are shown schematically as a set of tensile stress boundary curves (Figure 13).

Finally, the thermally induced stresses and the tensile strength of the HMA are compared over a range of temperatures in a failure envelope format (Figure 14). A flow chart representation of the low-temperature cracking characterization is shown in Figure 15.

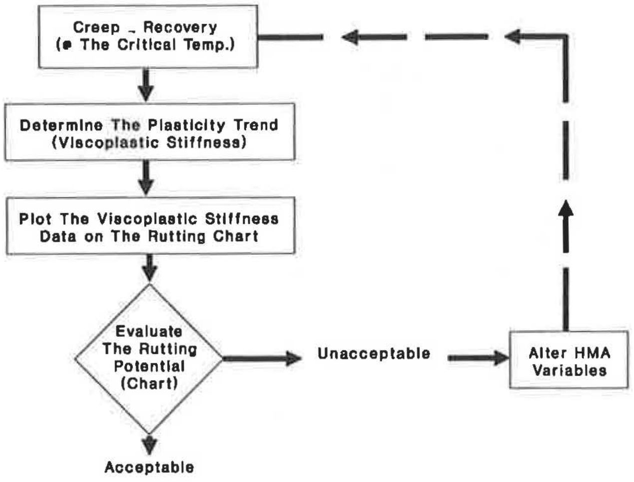


FIGURE 11 Flow chart describing rutting analysis subsystem.

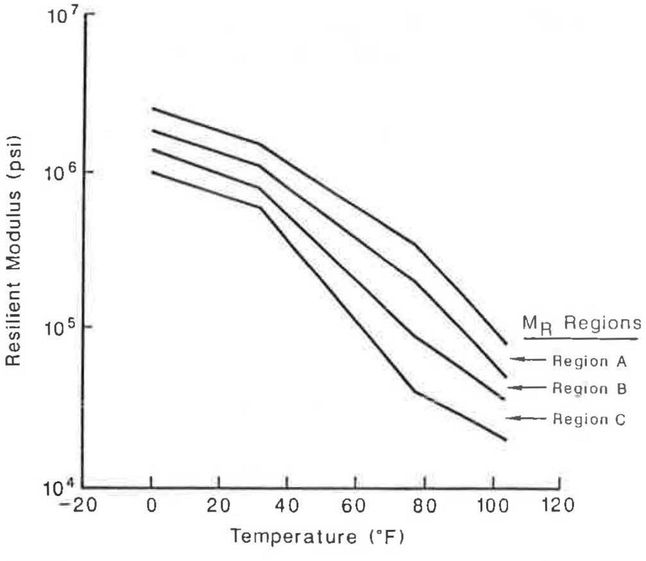


FIGURE 12 Schematic distribution of resilient modulus regions.

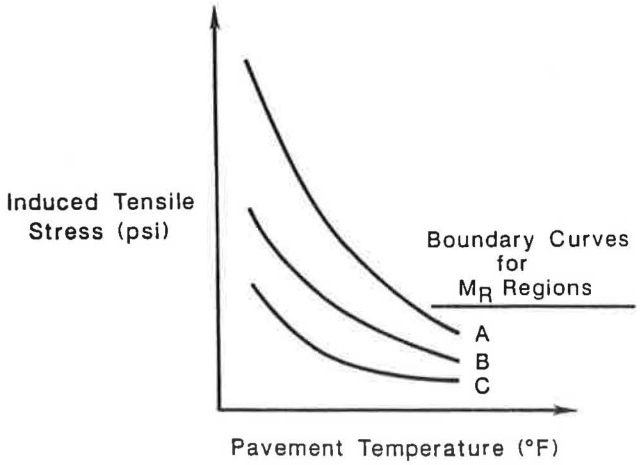


FIGURE 13 Schematic distribution of thermal stress versus pavement temperature for a given cooling rate.

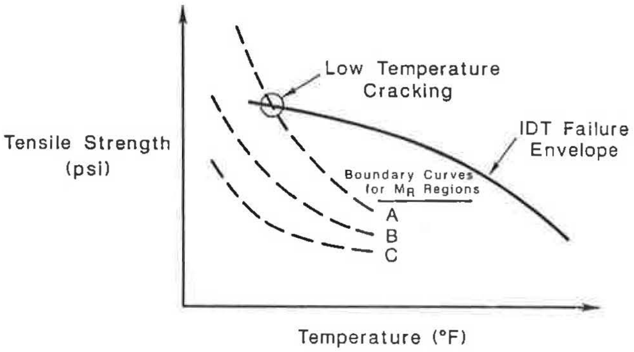


FIGURE 14 Procedure for evaluating thermal cracking potential using the indirect tensile failure envelope concept.

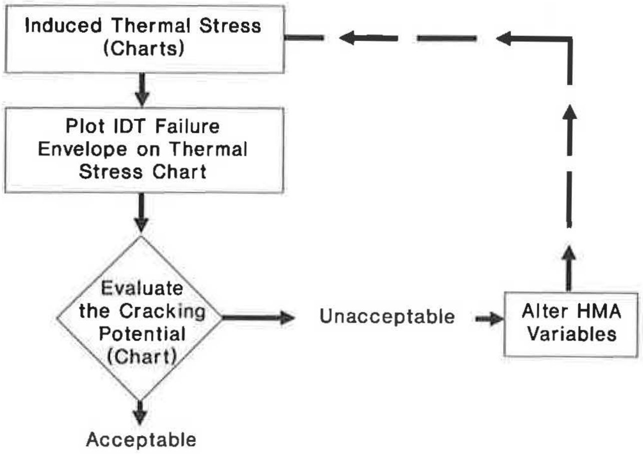
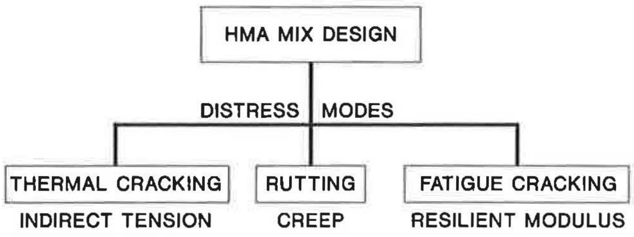


FIGURE 15 Flow chart describing thermal cracking analysis subsystem.

CONCLUSIONS AND RECOMMENDATIONS

HMA can be designed and analyzed using a rational approach. The methodology accounts for different modes of pavement distress (subgrade rutting, fatigue cracking, rutting, and low-temperature cracking) using fundamental engineering parameters. By using these mechanistic parameters in the mix design, structural pavement design may be integrated with the HMA mixture design (Figure 16).



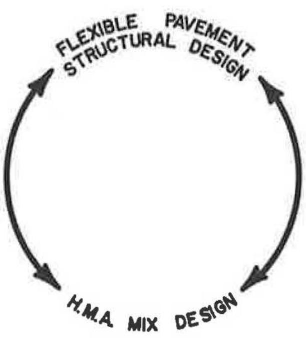


FIGURE 16 Integration of mix design and pavement design by using rational mixture characterization methodologies.

This procedure should be implemented on an interim basis, and the success or failure rates should be monitored. Standard procedures are needed for resilient modulus characterization of flexible pavement materials. Also, standards should be developed for a creep and permanent deformation test. Whenever possible, the creep test should be conducted at temperatures representative of field conditions. Shift factors should also be developed and used.

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