FINAL REPORT

IMPLEMENTATION OF THE FLORIDA CRACKING MODEL
INTO THE MECHANISTIC-EMPIRICAL
PAVEMENT DESIGN

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Prepared by:

Dr. Bjorn Birgisson, P.E., Associate Professor, Principal Investigator
Dr. Jianlin Wang, Research Assistant Professor
Dr. Reynaldo Roque, P.E., Professor, Co-Principal Investigator

Department of Civil and Coastal Engineering
University of Florida
Gainesville, Florida 32611-6580

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16. Abstract

Top-down cracking has been found to be a predominant mode of distresses of asphalt pavements in Florida. Therefore, it is important to accommodate top-down cracking in the design of asphalt mixtures and pavement structures. After a multi-year study on top-down cracking supported by the Florida Department of Transportation (FDOT), the University of Florida has developed a top-down cracking model based on the HMA fracture mechanics. This report presents the implementation of the Florida cracking model into a mechanistic-empirical (ME) flexible pavement design framework. Based on the Energy Ratio (ER) concept, a new ME pavement design tool for top-down cracking has been developed. In the Level 3 ME design, a series of material models were developed for estimation of the time-dependent material properties. With incorporation of the material properties models, the design tool is capable of performing pavement thickness design as well as pavement life prediction for top-down cracking in Florida. The thickness design is optimized for different traffic levels, mixture types, and binder selections. The AC thickness optimization is an automated process. This design tool has been developed into an interactive Windows-based software, making it convenient to use for Florida pavement design engineers.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometres	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		Temperature (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		Temperature (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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EXECUTIVE SUMMARY

This project implemented HMA Fracture Mechanics model and the Energy Ratio (ER) concept into the M-E Pavement Design Framework. The resulting design tool included all the essential features of the ME pavement design guide developed under NCHRP 1-37A. The HMA fracture mechanics model has the benefit of offering the potential integration of a pavement design model to the mixture specification and design. The pavement HMA fracture performance model has been calibrated for Florida conditions using existing pavement sections from the longitudinal wheel path cracking study. Both the HMA fracture mechanics model and the field work done in Florida were general and fundamental enough the address the differences in environment and pavement structure. The validation has been conducted primarily on pavements in Florida and materials and mixtures used in the Southeastern United States.

The energy ratio was used for Level 3 M-E top-down cracking design. The design premise is to ensure a reasonable predicted crack depth after a certain number of years. Based on the ER criterion for top-down cracking, which accounts for the structure and mixture for “averaged” environmental conditions, the design scenario is to determine the asphalt layer thickness for ER ≈ minimum required ER (or Optimum ER) at the end of the pavement design life, where the minimum required ER is determined based on the traffic level (design number of ESALs) and the reliability level for a particular pavement section to resist top-down cracking. The level 3 pavement design tool for top-down cracking developed based on the HMA Fracture Mechanics and the Energy Ratio is general in nature, allowing for the optimization of a pavement system for top-down cracking.

Seasonal variation in material properties are obtained from site-specific environmental conditions for pavements throughout Florida. A series of material property models were

developed correspondingly to obtain the key materials properties for Level 3 design, such as the dynamic modulus, the tensile strength, the creep parameters, and the dissipated creep strain energy (DCSE) limit. The development was mainly based on the incorporation of the dynamic modulus |E*| master curve. With incorporation of the material properties models, the design tool is capable of performing pavement thickness design as well as pavement life prediction for top-down cracking in Florida. The pavement thickness design was performed by seeking the optimum AC thickness that gives the minimum required Energy Ratio at the end of the pavement life. The pavement life calculation was to determine when the ER for the pavement section in consideration will drop to the minimum required value.

An interactive Windows-based mechanistic-empirical (M-E) pavement design software was developed for use by pavement engineers in Florida. The required inputs are minimum and most of the information can be generated from the default models embedded within the software. In this design software, the optimization of the AC layer thickness is an automatic process. The design tool was fully integrated with key mixture cracking properties and was capable of doing pavement life prediction for new, existing, and rehabilitated asphalt pavements. Due to the full integration of mixture properties and pavement thickness design, the design tool was developed independent of the current pavement design guide. This allows pavement design engineers to perform parallel comparisons with the predictions from MEPDG during the implementation phase.

1. INTRODUCTION

It is now well accepted that load-related top-down fatigue cracking (i.e., cracking that initiates at the surface of the pavement and propagates downward) commonly occurs in HMA pavements [1-6]. This phenomenon has been reported to occur in many parts of the United States, as well as in Europe, China, and other countries. Especially in Florida, it is discovered that over ninety percent cracking in asphalt pavements are in the form of top-down [3, 7, 8]. As an illustration, Figure 1.1 (a) and (b) show the typical top-down cracking observed from a Florida field section and a field core. This mode of failure cannot be explained by traditional fatigue mechanisms used to explain load-associated fatigue cracking that initiates at the bottom of the pavement. Among different types of cracking occurred in asphalt pavements (such as the bottom-up and top-down fatigue cracking, thermal cracking, reflective cracking), the top-down cracking seems to be the most complicated.

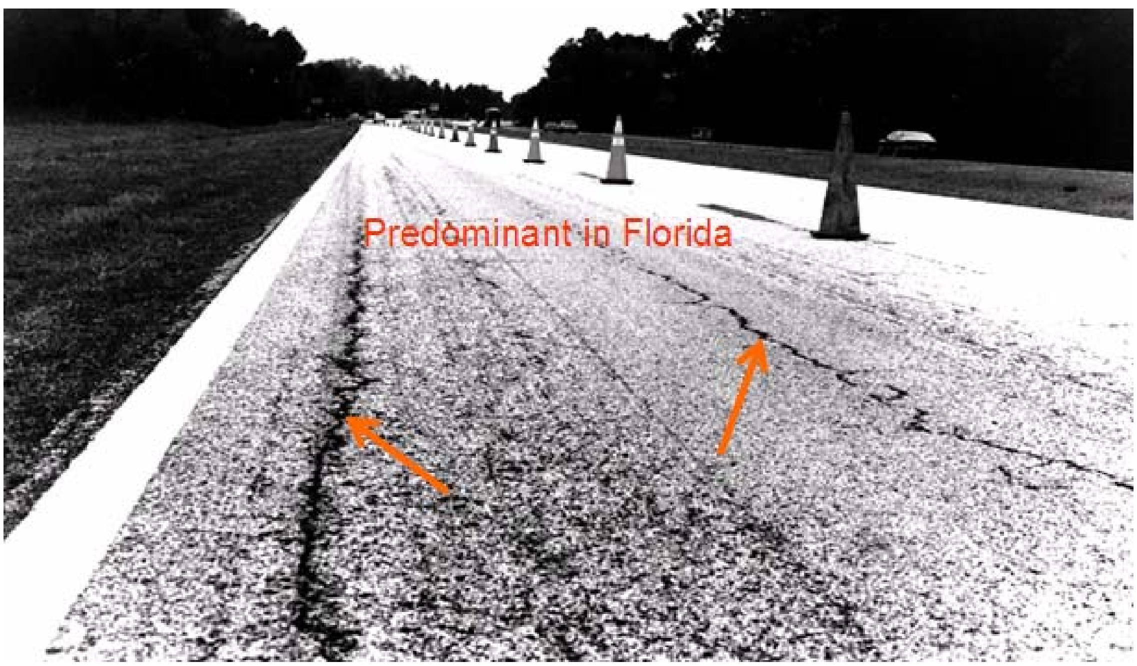


Figure 1.1a. Top down cracking observed from the field section

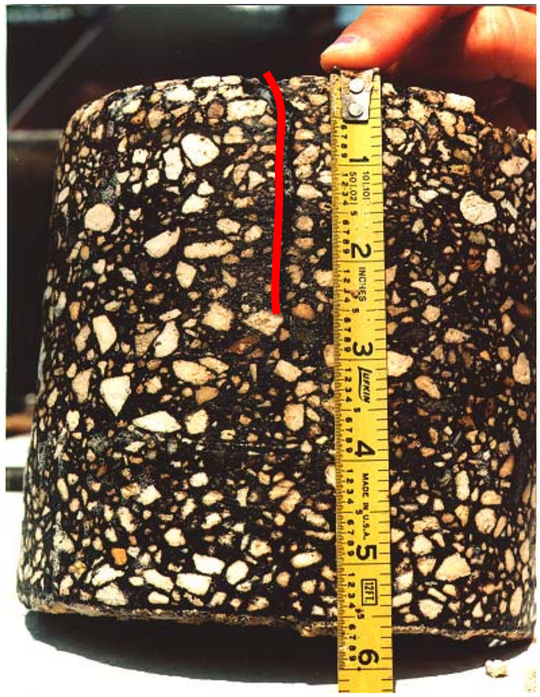


Figure 1.1b A field core

Along with the occurrence and propagation of the top-down cracks, pavement serviceability is significantly reduced. It is therefore necessary to develop suitable systems or models that would help to provide guidance for pavement engineers to select HMA mixtures and pavement structures that are most resistant to top-down fatigue cracking in specified loading and environmental conditions. It is also urgent to integrate the developed cracking models into the new mechanistic-empirical (M-E) pavement design developed under NCHRP 1-37A.

The new mechanistic-empirical (M-E) design combines the elements of mechanical modeling and performance observation in determining the required pavement life for a set of design conditions. The prediction of pavement life based on stresses and strains requires the ability to account for changes in loads, environmental and temperature effects and to track changes and damage in the material over the projected life span of a pavement. Empirical and/or mechanical performance models that relate predicted stresses and strains for given combination of loads, structure, and environmental conditions to rutting and cracking are also required in M-E design. Due to the recent recognition of top-down cracking as a major pavement distress mechanism, the MEPDG needs to include a procedure to evaluate the potential for top-down cracking.

2. CURRENT STATE OF KNOWLEDGE

The research team identified potential mechanisms and factors that could adequately explain the initiation and propagation of top-down cracks [7, 8]. Their work has indicated that the following factors appear to be primary contributors to the initiation of top-down cracks:

- Transverse contact stresses induced by radial truck tires. The researchers obtained measurements of contact stresses under radial truck tires that clearly indicated the presence of transverse tensile stresses. Analytical studies showed that these could generate tensile stresses at the surface of the pavement of sufficient magnitude to initiate cracks.
- Thermal stresses induced by cooling. Analytical and field studies have shown that thermal stresses appear to contribute to top-down crack initiation, even though these are not of sufficient magnitude to induce cracks in the absence of load-induced tensile stress.
- Age-hardening, which is greatest near the surface of the HMA layer, resulting in greater stiffness (higher stresses) and embrittlement (lower resistance to fracture). Mixtures with high stiffness and low strain tolerance have been clearly linked to inferior resistance to top-down cracking.

The research team also determined the mechanisms causing top-down cracks to initiate were not able to explain the propagation of top-down cracks below a depth of a few centimeters. Their field investigations, as well as those of others, clearly indicate that top-down cracks propagate to greater depths and sometimes through the entire depth of the surface layer. The research team continued their efforts to identify potential mechanisms and factors that could adequately explain the propagation of top-down cracks. Their work indicated that the following factors play a key role in the propagation of top-down cracks:

- Stiffness gradients within the asphalt layer induced by daily temperature fluctuations. Analytical work indicated that load-induced tensile stresses at the surface of the pavement were up to seven times greater when stiffness gradients were considered.
- The presence of a crack at the surface of the pavement. Whereas, load-induced tensile stresses were not predicted below a few centimeters when the pavement was modeled continuum (i.e., no crack is present), significant tensile stresses were predicted once the crack was introduced in the analysis. Therefore, the presence of the crack and its effect on stress redistribution within the pavement, is itself an essential part of capturing the mechanism of crack propagation.
- Changes in the transverse position of the load induced by tire wander. The location of the load relative to the length and position of the crack was found the have a strong effect on the development of tensile stresses that induce propagation of top-down cracks.
- Pavement structural characteristics. Although the effect of structure, specifically surface and base layer thickness and stiffness, does not appear to play a significant role in the initiation of top-down cracks, it does appear to play a strong role in the propagation of these cracks. This can be explained by the fact that loads further from the crack induce top-down crack propagation, whereas initiation is induced near the edge of the load.

The research team has recently performed a detailed analysis of the rheological behavior of asphalt mixtures and its effects on the pavement response using a viscoelastic boundary element method [8]. It is found that the rheological behavior of HMA mixture results in stress redistribution that may dominate the failure mode of the pavement structure. Pavements with different mixtures clearly exhibited different levels of top-down cracking performance for pavements with very similar structure, environmental and traffic conditions. In addition, identical pavements subjected to the same loading and environmental conditions, but with different friction course mixtures, indicated that more facture resistant friction courses resulted in pavements with superior resistance to top-down cracking. However, the researchers found that no single mixture property of characteristic is sufficient to assure adequate mixture performance. The following mixture properties have been determined to affect the mechanisms identified with top-down cracking initiation and propagation:

- Stiffness and creep compliance, which dictate the level of load and thermal stress development.
- Resistance to fracture, in terms of the mixture's resistance to either repeated load applications or the application of a single critical load event.
- Resistance to age-hardening.

In general, mixtures with lower stiffness, greater creep compliance, greater resistance to fracture, and lower rates of age-hardening will result in better performance. However, these properties are highly interrelated, such that it is difficult, if not impossible, to evaluate top-down cracking performance, even on a relative basis, by simply comparing these properties. These results appear to indicate that appropriate evaluation of top-down cracking performance of mixtures needs to be done within the context of an appropriate framework or model that can account for the effects of these properties on stress, strain, energy, and damage (cracking) development for specified design conditions (structure, environment, traffic, etc.).

Recent laboratory and field studies by the research team at the University of Florida have led to the development of a viscoelastic fracture mechanics-based crack growth law (HMA fracture mechanics) for asphalt mixtures [9, 10] that is capable of fully describing both initiation and propagation of cracks in asphalt mixtures for any combination of loading and temperature conditions. The model requires the determination of only four fundamental mixture parameters that can be obtained from less than one hour testing using the Superpave Indirect Tension Test (IDT). These parameters can account for micro-damage, crack propagation, and healing for stated loading conditions, temperatures, and rest periods. It should be noted that this model is based on fundamental properties, which means that mixture properties are independent of model of loading and test method. This is a critical feature as it allows for the consideration of the combined effects of temperature and load-induced stresses on the development of damage and fracture.

Field investigations performed on more than 20 test sections across the state of Florida have shown that the HMA fracture mechanics model was able to accurately rank their relative top-down cracking performance by accounting for such factors as mixture properties, thermal stresses, and pavement structure. These studies clearly indicated that no single mixture property or characteristic was able to rank the relative performance for different conditions.

Based on the HMA Fracture Mechanics Model, the research team has identified a parameter termed the Energy Ratio (ER) [7], which was determined to accurately distinguish between pavements that exhibited top-down cracking and those that did not, except for mixtures with excessively low or unusually high dissipated creep strain energy thresholds. The Energy Ratio (ER), defined as the dissipated creep strain energy threshold of the mixture divided by the minimum dissipated creep strain energy required, is determined on the basis of tensile properties that can be obtained from a modulus, creep, and strength test performed with the Superpave IDT at a temperature of 10°C. The Energy Ratio accounts for the effects of pavement structural characteristics on top-down cracking performance. Therefore, it can be used to suitably integrate asphalt mixture properties in the pavement design process. In addition, a rational approach was developed to adjust the minimum Energy Ratio criterion for different traffic level pavements. The ER model has been calibrated and evaluated using field sections from throughout the state of Florida.

3. Objectives and Approach

3.1 Objectives

This project implemented HMA Fracture Mechanics model and the Energy Ratio concept into the M-E Pavement Design Framework. The resulting design tool included all the essential features of the MEPDG developed under NCHRP 1-37A. The HMA fracture mechanics model has the benefit of offering the potential integration of a pavement design model to the mixture specification and design. The pavement HMA fracture performance model has been calibrated for Florida conditions using existing pavement sections from the longitudinal wheel path cracking study. Seasonal variation in material properties are obtained from site-specific environmental conditions for pavements throughout Florida. A level 3 pavement design tool for top-down cracking developed based on the HMA Fracture Mechanics and the Energy Ratio is general in nature, allowing for the optimization of a pavement system for top-down cracking. The primary objects of this research are summarized as follows:

- Develop a pavement cracking analysis framework for evaluating the cracking performance of mixtures. This framework is implemented using existing modeling capabilities that allow for the presence of a crack in the pavement. This framework is compatible with the new M-E Pavement Design Guide under NCHRP 1-37A. In addition, it includes a suitable material model based on HMA fracture mechanics for implementation into an M-E design framework.

- Develop an interactive Windows-based M-E pavement design tool for use by pavement engineers in Florida. The pavement thickness design is fully integrated with key mixture cracking properties. Due to the full integration of mixture specification and pavement thickness design, the design tool developed is independent of MEPDG, even though the essential features of the current MEPDG are included.

The developed model uses critical design conditions, material model, and pavement analysis model and calibrated cracking performance equations for Florida conditions.

3.2 Approach

A brief detail of work done, to meet all the objectives of this project are described in following sections.

Task 1: Identify / Develop a General Framework for Cracking Evaluation of HMA Mixtures

A framework for the cracking evaluation of HMA pavements was developed. In this framework, the essential components needed to obtain the desired outcome of the system are:

- Key mixture properties
- Essential environmental information (such as the mean annual air temperature)
- Traffic and load information
- Reliability input
- Mixture master curves that describe the key mixture properties over the required range of temperature and loading times
- Global aging model that takes into account the age-hardening of mixture
- HMA fracture mechanics and energy ratio models

Task 2: Material Property Models

One of the key tasks is to determine the material properties for pavement design and pavement life calculation. In this task, a series of material property models was developed correspondingly to obtain the key materials properties for Level 3 design, such as the dynamic modulus, the tensile strength, the creep parameters, and the energy limit. The development is mainly based on the incorporation of the dynamic modulus |E*| master curve. These properties were used to calculate the pavement response and to evaluate the cracking performance.

Task 3: Integration of HMA Fracture Mechanics and Energy Ratio Models

The research team integrated HMA fracture mechanics into Level 3 pavement design. The key model parameters required to describe the HMA fracture model are fundamental and are obtained from the material properties model developed in Task 2. The pavement responses (stresses and strains) are obtained from the Layered Elastic Analysis. The Energy Ratio is used to criterion for AC thickness optimization and for pavement life calculation. The traffic and reliability information was used to determine the minimum Energy Ratio required for a particular pavement section to resist top-down cracking. The pavement thickness design was performed by seeking the optimum AC thickness that gives the minimum required Energy Ratio at the end of the pavement life. The pavement life calculation was to determine when the ER for the pavement section in consideration will drop to the minimum required value.

Task 4: Integration of Calibrated Cracking Performance System for Florida Conditions

Field investigations performed on more than 30 test sections from the longitudinal wheel path cracking study from across Florida have shown that the HMA fracture mechanics model was able to accurately rank their relative performance. Both the HMA fracture mechanics model and the field work done in Florida were general and fundamental enough the address the differences in environment and pavement structure. The validation has been conducted primarily on pavements in Florida and materials and mixtures used in the Southeastern United States. Based on the work to date and using the results from the material model and the pavement analysis model, the resulting calibrated cracking performance system was integrated into a Windows-based interactive design tool, and tailored for Florida conditions.

Task 5: Development of an Interactive Windows-Based Design Tool for New and Rehabilitated Pavements

In this task, an interactive Windows-based mechanistic-empirical (M-E) pavement design tool was developed for use by pavement engineers in Florida. It could be used for new pavement design as well as for pavement rehabilitation. In this design tool, the AC thickness optimization is an automatic process. The design tool was fully integrated with key mixture cracking properties and was capable of doing pavement life prediction for new, existing, and rehabilitated asphalt pavements. Due to the full integration of mixture properties and pavement thickness design, the design tool was developed independent of the MEPDG. This allows pavement design engineers to perform parallel comparisons to the predictions from MEPDG during the implementation phase.

4. FLORIDA TOP-DOWN CRACKING MODEL

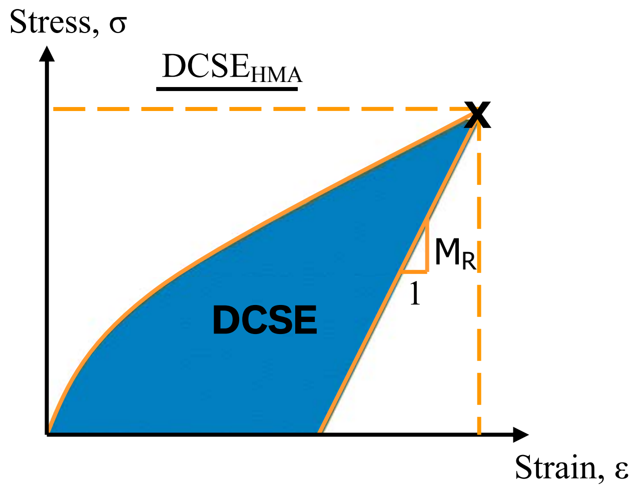
Conventional pavement analysis models are incapable of predicting pavement responses that could result in stress-strain conditions that would explain the initiation and propagation of top-down longitudinal cracks. Most these models that predict the bending stresses in a layered pavement system only consider the instantaneous elastic response but ignore the delayed elastic and creep behavior of the asphalt layer. According the numerical work by research team [8] and the experimental study done by Tamagny et al. [11], the rheological behavior of the asphalt mixtures results in stress redistribution in the pavement system and thus accumulated viscoelastic residual stresses due to continuous repeated loads. A valid pavement cracking model should be taken into consideration the viscoelastic properties of asphalt mixtures.

The research team has developed a fundamental crack growth law based on the principles of viscoelastic fracture mechanics. This law has been incorporated into a cracking model called the HMA Fracture Mechanics Model. The model development and its features were well documented in [9] and [10]. The HMA fracture mechanics model allows for prediction of crack initiation and crack growth in asphalt mixture subjected to any specified loading history. The Florida top-down cracking model was built by introducing the energy ratio concept [7] into the HMA fracture mechanics. A brief description of the model's key features and the energy ratio concept is given below.

4.1 Key Features of the Florida Cracking Model

The key features of the Florida cracking model are summarized below:

- Damage in asphalt mixture is equal to the accumulated dissipated creep strain energy (DCSE);
- There exists a damage threshold (called DCSE threshold or DCSE limit, illustrated in Figure 4.1) in asphalt mixture that is independent of loading model or loading history;
- Damage under the cracking threshold is fully healable;
- Once the damage (accumulated DCSE) exceeds the damage threshold (DCSE limit), macro-crack will initiate, or propagate is the crack is already present;
- Macro-crack is not healable.

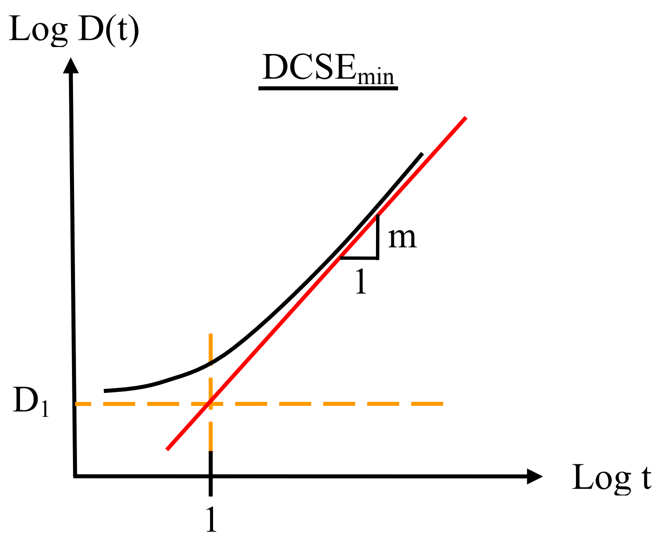


$\text{DCSE}_{HMA} = \text{AREA}$

Figure 4.1 Graphic illustration of the DCSE

The HMA fracture mechanics suggests that the dissipated creep strain energy (DCSE) limit of asphalt mixtures suitably defines a fracture damage threshold. Damage below the threshold is considered micro-damage (i.e., damage not associated with crack initiation or crack growth) and appears to be fully healable after a resting period, while macro-damage (i.e., damage associated with crack initiation or growth), which does not appear to be healable, occurs when the damage exceeds the threshold. An external load induces the damage increment in the asphalt mixture in the form of strain energy that is dissipated into micro-cracks. Thus the rate of damage increment depends not only on the load magnitude, but also the viscoelastic properties of the mixture.

According to the Florida cracking model, the initiation and propagation of cracks in asphalt mixtures can be determined for any loading condition by calculating the amount of dissipated creep strain energy and comparing the accumulated DCSE with the DCSE threshold of the mixture. The calculation of DCSE needs the structural properties (used to determine the tensile stress) and the material properties D1 and m-value, which are parameters in the creep compliance function $D(t) = D_0 + D_1 * t^m$, as illustrated in Figure 4.2.



$$DCSE_{min} = m^{2.98} D_1 / f(\sigma_t, S_t)$$

Figure 4.2 Graphic illustration of the creep compliance curve and the $DCSE_{min}$

4.2 Energy Ratio Concept

The research team had investigated more than thirty field test sections throughout the state of Florida. Thorough analyses were conducted to evaluate the effects of mixture properties on top-down cracking performance. The research team was trying to search for a criterion (such as the mixture tensile strength, creep compliance, the m-value the measures the creep rate, the binder viscosity, and so on) that could be used to evaluate the pavement cracking performance. The analysis results indicated that there is no single mixture property that could reliably identify pavements that exhibited poor top-down cracking (i.e., no single property of set of properties was strongly correlated to top-down cracking performance). This was true even when comparing mixture properties between paired sections with nearly identical traffic conditions. In general, mixtures with lower stiffness, greater creep compliance, greater resistance to fracture (higher DCSE limit), and lower rate of age-hardening will result in better performance. However, these mixture properties are highly interrelated so that it is difficult to evaluate top-down cracking performance, even on a relative basis, simply by comparing these properties.

Figure 4.3 illustrates the basic principles involved for two mixtures with different properties. For either mixture, the dissipated creep strain energy (DCSE) increases with number of load applications (ESALs). Mixtures with higher creep compliance power law parameters (m-value and D_1) will exhibit a higher rate of dissipated creep strain energy accumulation.

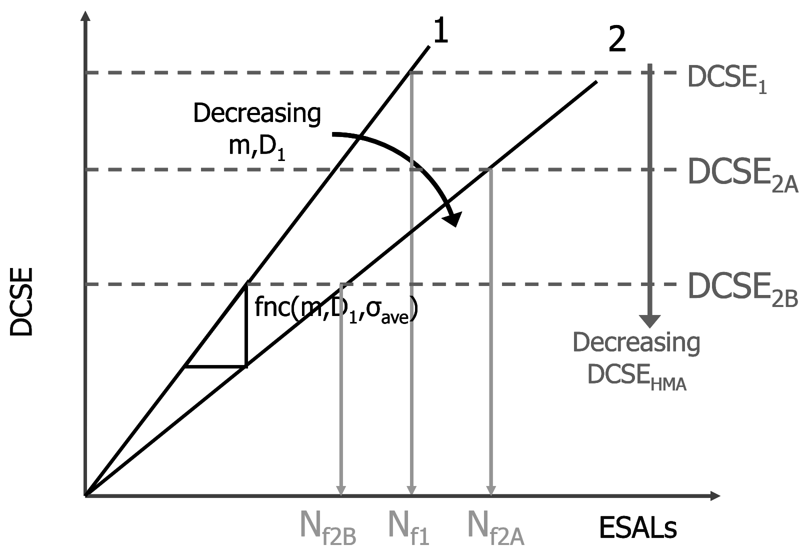


Figure 4.3 Basic principles of HMA fracture mechanics model

However, this does not necessarily imply that cracks will initiate or propagate more quickly in these mixtures, as this will depend on the energy threshold, which varies significantly between mixtures and is not necessarily related to the creep characteristics of the mixture. As shown in Figure 4.3, mixture 1 may crack at less number of loads or at greater number of loads than mixture 2, depending on the energy thresholds of the two mixtures. Mixture 2 will crack before mixture 1 if it has a low energy threshold ($DCSE_{2B}$), but will crack after mixture one if it has a higher energy threshold ($DCSE_{2A}$). Of course, it assumes that both mixtures are subjected to the same level of tensile stress. The example presented above illustrates the value of the HMA fracture mechanics model in properly and accurately evaluating the cracking performance of asphalt mixture. This work has clearly shown that no single asphalt mixture property can be used to predict mixture cracking performance reliably.

Without being able to identify a criterion based on mixture properties for prediction of pavement cracking performance, Roque and collaborators turned to energy consideration. Based on the resilient modulus and strength tests, the total fracture energy (FE) and the dissipated creep strain energy (DCSE) were calculated for all test sections. It was found that energy by itself did not accurately predict the performance of pavement sections. Considering the fact that tensile stresses in the AC layer are important for evaluation of cracking performance, it was necessary to include the influence of pavement structure. For example, thinner pavements are more likely to experience cracking because stress levels in these pavements are typically higher. Figure 4.4 shows the AC thicknesses of twenty-two field sections tested. Although there was no general trend in the AC thickness versus the cracking performance, it was observed that most of the pavements with AC thickness less than 5 inches were cracked. The average AC thickness of the twenty-two field sections is 5.6 inches. Moreover, pavements with stiffer bases were unlikely to crack. These observations convinced the research team that the structural effects need to be taken into account in addition to the energy consideration.

Based the above work, Roque et al. [7] introduced a parameter termed the energy ratio into the HMA Fracture Mechanics Model. This parameter, in conjunction with the DCSE limit, was found to accurately distinguish between pavements that exhibited top-down cracking and those that did not. The energy ratio is a dimensionless parameter defined as the dissipated creep strain energy threshold of the mixture divided by the minimum dissipated creep strain energy required:

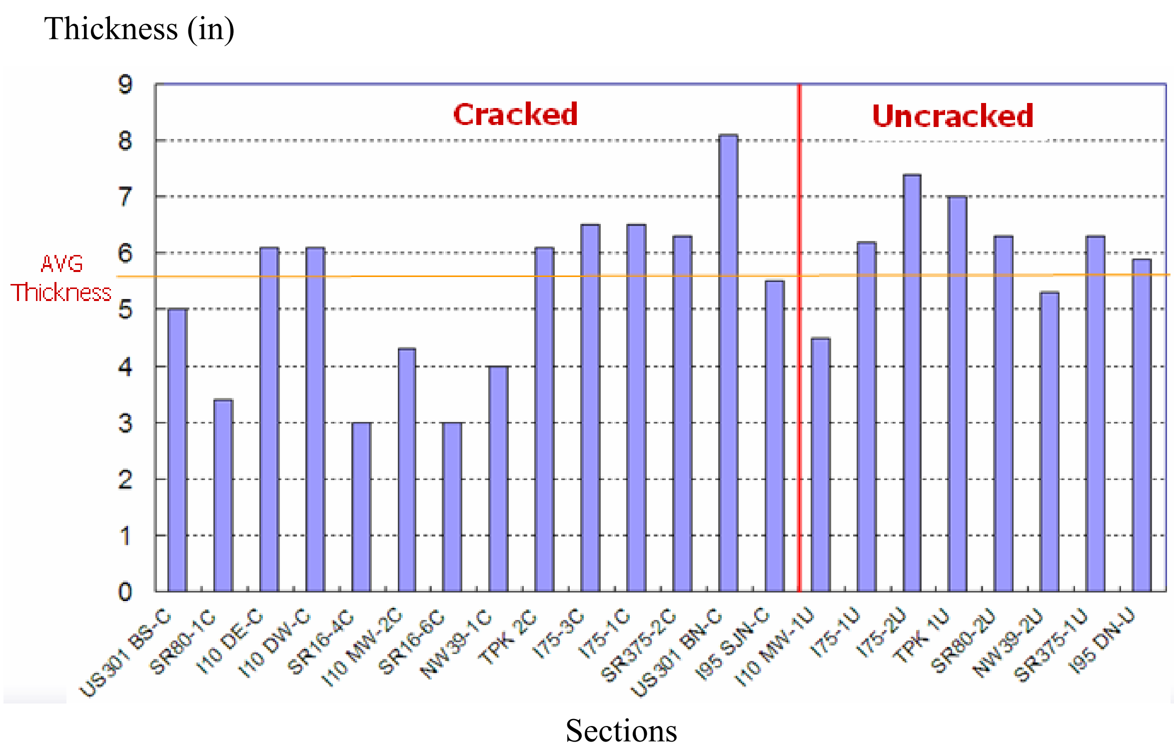


Figure 4.4 Thicknesses of pavement sections tested

$$ER = DCSE_f / DCSE_{min} \quad (4.1a)$$

where $DCSE_f$ is dissipated creep strain energy threshold (denoted by the shaded area in Figure 4.1), and $DCSE_{min}$ is defined as the minimum dissipated creep strain energy. Roque et al. [7] expressed the relation between DCSEmin and the creep parameters D_1 and m-value in a single function as (Figure 4.2):

$$DCSE_{min} = m^{2.98} * D_1 / f(S_t, \sigma_{max}) \quad (4.1b)$$

where m and D_1 are the creep compliance parameters, and the function $f(S_t, \sigma_{max})$ can be expressed as

$$f(S_t, \sigma_{max}) = 0.0299 * \sigma_{max}^{-3.10} * (6.36 - S_t) + 2.46 * 10^{-8} \quad (4.1c)$$

where S_t is the tensile strength (in MPa), and σ_{max} is the maximum tensile stress (in psi).

Based on Energy Ratio concept, two energy-based criteria were recommended to control top-down cracking of hot mix asphalt: 1) a minimum dissipated creep strain energy threshold (say 0.75 kJ/m^3); and 2) a minimum ER for mixtures with a DCSE threshold greater than the minimum. The minimum ER required should be adjusted for different traffic levels and different reliabilities (i.e., the minimum ER should be greater for pavements with higher traffic levels and/or higher reliability). The research team has developed a general formula to determine the minimum required (optimum) ER for a pavement section by introducing a traffic factor and a resistance (reliability) factor, which will be discussed further in the next section. Figure 4.5 shows that for almost all 22 field test sections, the above criteria successfully separated uncracked sections from those that exhibited top-down cracking. The ER accounts for both the effects of pavement structural characteristics and the effects of creep properties of the mixture on top-down cracking performance. Therefore, it could be used to suitably integrate asphalt mixture properties in the pavement design process.

4.3 Traffic and Reliability Factors

As mentioned in the previous section, it is necessary to determine the minimum required (optimum) ER for a pavement section in the evaluation of its top-down cracking performance by using the ER criterion. In this consideration, it quickly became evident that traffic and reliability level would need to be considered. Obviously, a pavement with more load applications and higher reliability would require a mixture with higher minimum Energy Ratio. The procedure for determining the potential of a pavement to resist top-down cracking adopted by the research team is described below.

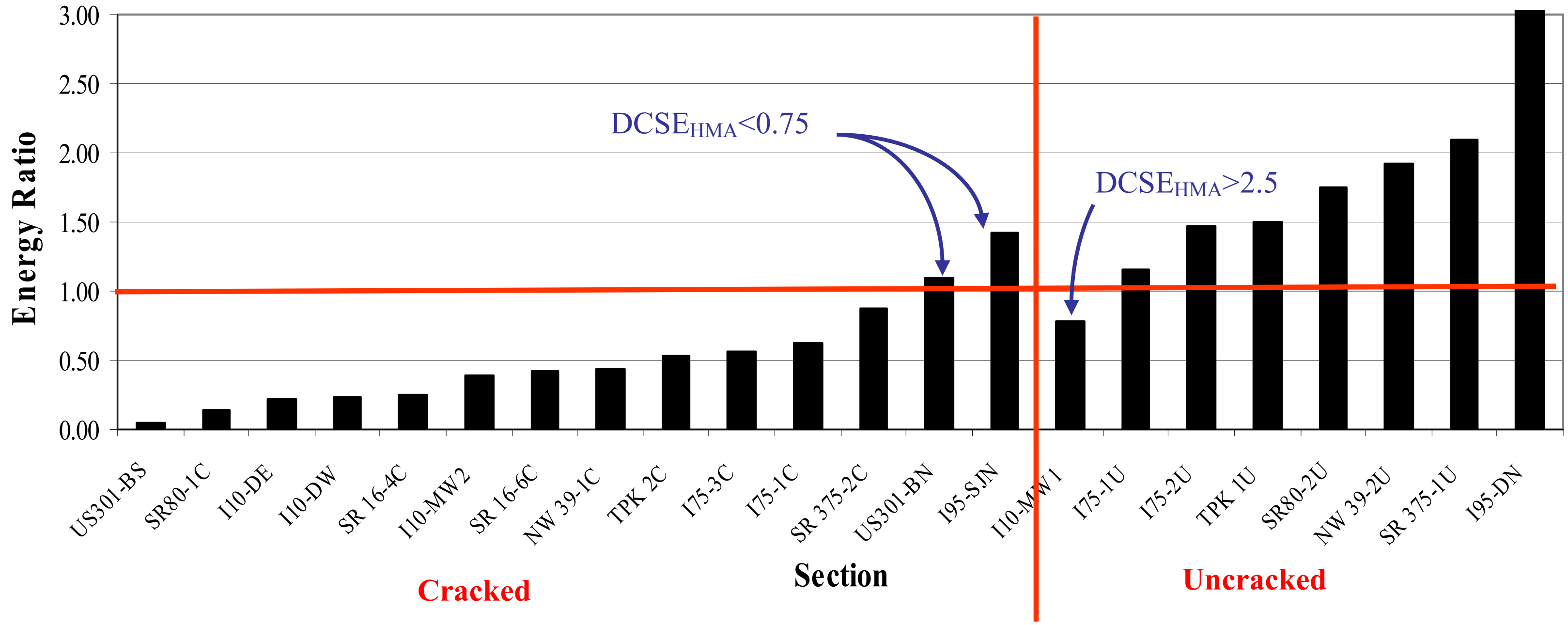


Figure 4.5 Energy ratio for 22 field test sections

From the entire field sections tested, the uncracked section with the lowest Energy Ratio greater than 1.0 (I75-1U, ER = 1.20) was selected for calibration. The traffic level for the section was 500,000 ESAL/year, which results in a total design number of ESALs equal to 10 million for a design life of 20 years. Based on the I-75 design, ER=1.2 was calibrated design traffic ESALs = 10 million and reliability R= 95%.

For section I75-1U, the based design parameters were given as:

S_0	ΔPSI	a_1	S_t (MPa)	m	D_1 (psi^{-1})	$DCSE_f$ (kJ/m^3)
0.35	2	0.44	2.01	0.417	9.89E-07	1.81

where:

S_0: standard deviation;

ΔPSI: design serviceability loss;

a_1: structural coefficient of AC layer;

S_t (Mpa): tensile strength of AC layer;

m and D_1: creep compliance parameters;

$DCSE_f$: dissipated creep strength energy of mixture;

Some assumptions and procedures for the design calculations were described below:

1. The AC layer's thickness (6.2 in) for the I75-1U section was the thickness under reliability 95%.
2. The tensile stress at the bottom of AC layer was calculated based on the following structure:

   AC layer: AC layer's thickness, AC modulus 1852 ksi;

   Base layer: thickness 12", modulus 64 ksi;

Stabilized subgrade: thickness 12”, modulus 51 ksi;

Embankment: semi-infinite layer, modulus 36 ksi.

3. The tensile stress at the bottom of AC layer was calculated using KENLAYER program with the applied input stress 79.6 psi and radius 6 in.
4. Equations used in the calculation were

$$\log W_{18} = Z_R S_0 + 9.36\log(SN+1) - 0.20 + \frac{\log\left[\Delta PSI/(4.2-1.5)\right]}{0.4 + 1094/(SN+1)^{5.19}} + 2.32\log E_R - 8.07 \tag{4.2}$$

where:

W_{18} : ESALs in 20 years;

Z_R : Standard normal deviate;

S_0 : Standard deviation;

SN : Structural number;

ΔPSI : Design serviceability loss;

E_R : Modulus of subgrade.

$$SN = SN_1 + SN_2 + SN_3$$

$$SN_1 = a_1 H_1;\ SN_2 = a_2 c_2 H_2;\ SN_3 = a_3 c_3 H_3$$

where c_i and H_i are the drainage coefficient and the thickness of each layer, respectively (with i = 1 representing the AC layer, and so on) and the energy ratio equation:

$$ER = \frac{DCSE_f}{DCSE_{\min}};$$

where,

$$DCSE_f = FE - \frac{1}{2}\frac{S_t^2}{M_R};$$

$$DCSE_{min} = m^{2.98} * D_1 / A;$$

$$A = 0.0299 * \sigma^{-3.10}(6.36 - S_t) + 2.46 * 10^{-8};$$

The following table (Table 4.1) summarizes the detailed results of these calculations:

Table 4.1 Calculation of the Energy Ratio values based on the design for the I-75U section

ESALs (in 20 years) = 50000*20 = 1 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	1.59	3.61	243.10	2.98E-08	2.45	0.74
70	-0.524	36000	1.71	3.88	231.30	3.07E-08	2.38	0.76
75	-0.674	36000	1.74	3.96	228.00	3.10E-08	2.36	0.77
80	-0.841	36000	1.78	4.05	224.10	3.13E-08	2.33	0.78
85	-1.037	36000	1.83	4.17	219.10	3.18E-08	2.29	0.79
90	-1.282	36000	1.90	4.31	213.40	3.24E-08	2.25	0.80
95	-1.645	36000	1.99	4.52	205.10	3.35E-08	2.18	0.83
99	-2.327	36000	2.18	4.95	189.20	3.60E-08	2.03	0.89
ESALs (in 20 years) = 100000*20 = 2 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	1.69	3.84	234.50	3.04E-08	2.40	0.76
70	-0.524	36000	1.82	4.13	220.80	3.16E-08	2.31	0.78
75	-0.674	36000	1.85	4.21	217.40	3.20E-08	2.28	0.79
80	-0.841	36000	1.90	4.31	213.40	3.24E-08	2.25	0.80
85	-1.037	36000	1.95	4.42	209.00	3.30E-08	2.21	0.82
90	-1.282	36000	2.01	4.57	203.10	3.37E-08	2.16	0.84

95	-1.645	36000	2.11	4.80	194.50	3.50E-08	2.08	0.87
99	-2.327	36000	2.31	5.25	178.90	3.81E-08	1.91	0.95
ESALs (in 20 years) = 400000*20 = 8 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	2.13	4.84	194.10	3.51E-08	2.08	0.87
70	-0.524	36000	2.28	5.19	181.80	3.75E-08	1.95	0.93
75	-0.674	36000	2.33	5.30	177.30	3.85E-08	1.90	0.95
80	-0.841	36000	2.38	5.41	173.70	3.94E-08	1.85	0.98
85	-1.037	36000	2.44	5.55	169.30	4.06E-08	1.80	1.01
90	-1.282	36000	2.52	5.73	163.90	4.23E-08	1.72	1.05
95	-1.645	36000	2.64	6.00	156.10	4.52E-08	1.61	1.12
99	-2.327	36000	2.88	6.55	141.70	5.25E-08	1.39	1.30
ESALs (in 20 years) = 500000*20 = 10 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ(psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	2.21	5.02	186.70	3.64E-08	2.00	0.90
70	-0.524	36000	2.37	5.38	174.70	3.92E-08	1.86	0.97
75	-0.674	36000	2.42	5.49	171.20	4.01E-08	1.82	0.99
80	-0.841	36000	2.47	5.61	166.70	4.14E-08	1.76	1.03
85	-1.037	36000	2.53	5.75	163.30	4.25E-08	1.72	1.06
90	-1.282	36000	2.61	5.94	158.50	4.43E-08	1.65	1.10
95	-1.645	36000	2.74	6.22	148.80	4.85E-08	1.50	1.20
99	-2.327	36000	2.98	6.78	136.20	5.61E-08	1.30	1.39
ESALs (in 20 years) = 700000*20 = 14 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER

50	0	36000	2.34	5.32	177.50	3.85E-08	1.90	0.95
70	-0.524	36000	2.50	5.68	166.90	4.14E-08	1.76	1.03
75	-0.674	36000	2.55	5.79	162.10	4.30E-08	1.70	1.07
80	-0.841	36000	2.60	5.92	157.00	4.49E-08	1.63	1.11
85	-1.037	36000	2.67	6.07	154.20	4.60E-08	1.59	1.14
90	-1.282	36000	2.76	6.26	149.60	4.81E-08	1.52	1.19
95	-1.645	36000	2.89	6.56	140.90	5.29E-08	1.38	1.31
99	-2.327	36000	3.15	7.15	127.90	6.29E-08	1.16	1.56
ESALs (in 20 years) = 1000000*20 = 20 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	2.47	5.61	167.50	4.12E-08	1.77	1.02
70	-0.524	36000	2.65	6.02	154.10	4.61E-08	1.58	1.14
75	-0.674	36000	2.70	6.13	152.50	4.68E-08	1.56	1.16
80	-0.841	36000	2.76	6.26	148.40	4.87E-08	1.50	1.21
85	-1.037	36000	2.83	6.42	144.90	5.06E-08	1.44	1.25
90	-1.282	36000	2.92	6.63	140.90	5.29E-08	1.38	1.31
95	-1.645	36000	3.05	6.94	132.80	5.87E-08	1.24	1.45
99	-2.327	36000	3.32	7.56	119.00	7.25E-08	1.01	1.80
ESALs (in 20 years) = 1200000*20 = 24 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	2.55	5.79	162.10	4.30E-08	1.70	1.07
70	-0.524	36000	2.72	6.19	150.90	4.75E-08	1.54	1.18
75	-0.674	36000	2.78	6.31	147.80	4.90E-08	1.49	1.22
80	-0.841	36000	2.84	6.45	144.20	5.10E-08	1.43	1.26
85	-1.037	36000	2.91	6.61	140.20	5.34E-08	1.37	1.32

90	-1.282	36000	3.00	6.82	135.30	5.67E-08	1.29	1.41
95	-1.645	36000	3.14	7.14	128.10	6.27E-08	1.16	1.55
99	-2.327	36000	3.42	7.77	115.40	7.72E-08	0.94	1.92
ESALs (in 20 years) = 1500000*20 = 30 million								
R (%)	Z_R	E_R (psi)	SN_1	$H_{(AC)}$ (in)	σ (psi)	A	$DCSE_{min}$ (kJ/m^3)	ER
50	0	36000	2.64	6.00	156.10	4.52E-08	1.61	1.12
70	-0.524	36000	2.82	6.41	145.20	5.04E-08	1.45	1.25
75	-0.674	36000	2.88	6.54	141.90	5.23E-08	1.39	1.30
80	-0.841	36000	2.94	6.68	138.50	5.45E-08	1.34	1.35
85	-1.037	36000	3.01	6.85	134.60	5.73E-08	1.27	1.42
90	-1.282	36000	3.11	7.06	129.80	6.12E-08	1.19	1.52
95	-1.645	36000	3.25	7.39	122.90	6.79E-08	1.07	1.68
99	-2.327	36000	3.54	8.04	110.50	8.48E-08	0.86	2.10

Based on the calculations presented in Table 4.1, the energy ratio values for the I-75U section corresponding to different traffic and reliability levels were summarized in Table 4.2. The relation between the ER and the traffic and reliability levels is plotted in Figure 4.6. It is observed from Table 4.2 that ER = 1.2 corresponds to the case where design number of ESALs = 10 million and the reliability level is equal to 95%. This was the one used for calibration.

Table 4.2 The Energy Ratio values for the I-75U section corresponding to different traffic and reliability levels

	Reliability (%)	50	70	75	80	85	90	95	99
ESALs	1.40E+06	0.74	0.76	0.77	0.78	0.79	0.80	0.83	0.89
	2.00E+06	0.76	0.78	0.79	0.80	0.82	0.84	0.87	0.95
	8.00E+06	0.87	0.93	0.95	0.98	1.01	1.05	1.12	1.30
	1.00E+07	0.90	0.97	0.99	1.03	1.06	1.10	1.20	1.39
	1.40E+07	0.95	1.03	1.07	1.11	1.14	1.19	1.31	1.56
	2.00E+07	1.02	1.14	1.16	1.21	1.25	1.31	1.45	1.80
	2.40E+07	1.07	1.18	1.22	1.26	1.32	1.41	1.55	1.92
	3.00E+07	1.12	1.25	1.30	1.35	1.42	1.52	1.68	2.10

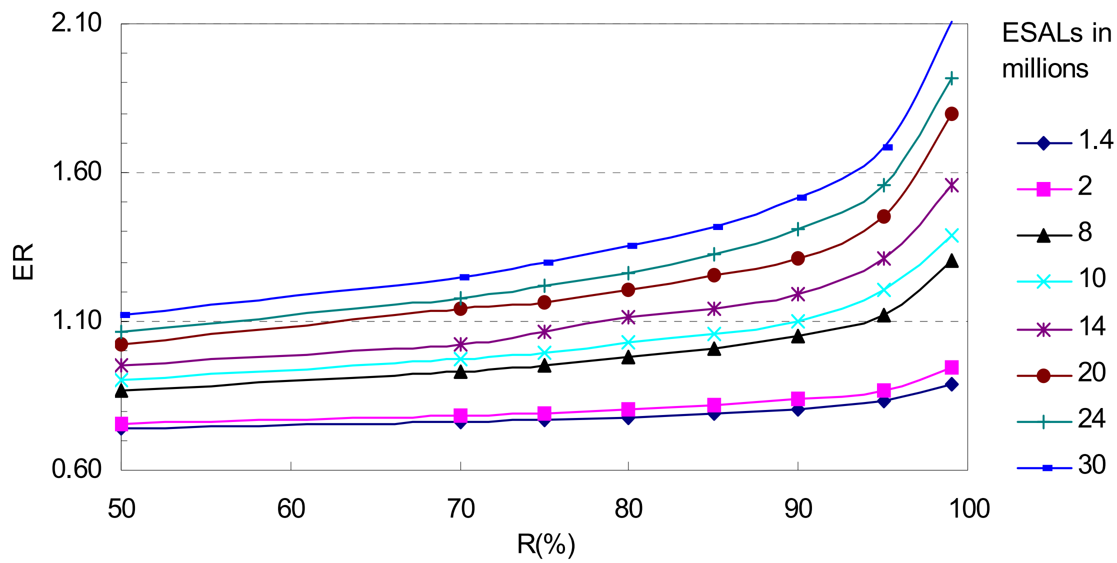


Figure 4.6 Variation of the energy ratio with the reliability level for different traffic levels (number of ESALs)

The relation plotted in Figure 4.6 shows that the energy ratio increases as the reliability increases, which indicates a higher resistance to cracking is required for the mixtures. Similarly, for a given reliability level, higher traffic level requires a higher energy ratio, which is because in the design process, a greater loading always results in a thicker AC layer. The ER values in Table 4.2 can also be plotted as a function of the number of ESALs for different reliability levels, as shown in Figure 4.7. It can be observed from this figure that the ER is approximately a linear function of the number of ESALs. As a result, the ER curves plotted in Figure 4.7 were fitted into linear functions of the design number of ESALs (in 10 million) for different reliability levels, with the expressions listed in Table 4.3.

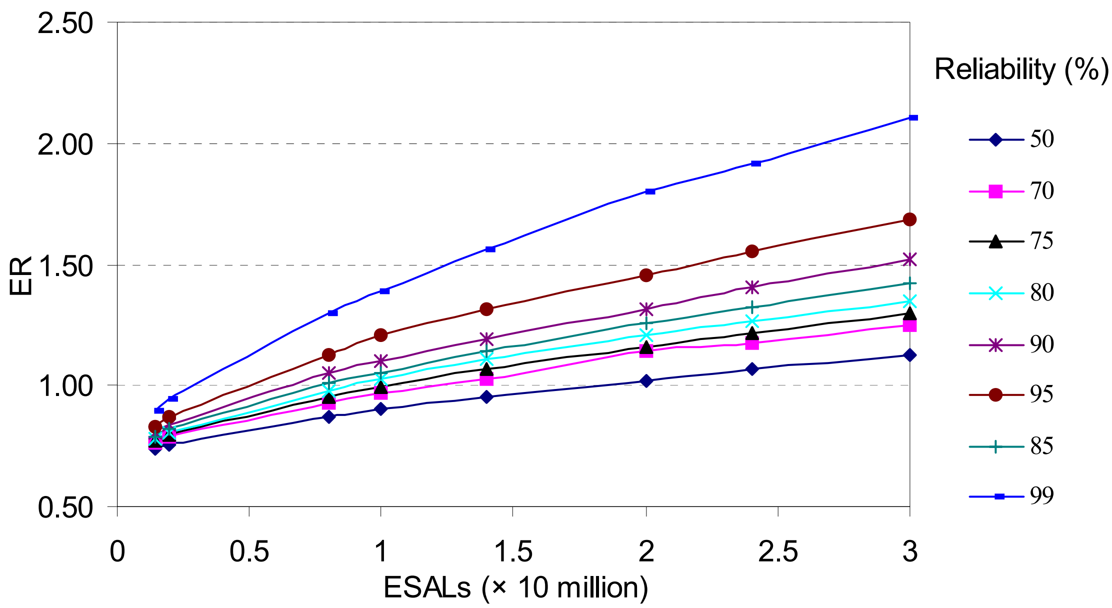


Figure 4.7 Variation of the Energy Ratio with the design number of ESALs (in 10 million) for different reliability levels

Table 4.3 The fitted ER as linear functions of the design number of ESALs (in 10 million) for different reliability levels

Reliability (%)	ER = f (ESALs in 10 millions)	R^2
99	$y = 0.4224\,x + 0.9105$	0.9814
95	$y = 0.2957\,x + 0.8496$	0.9768
90	$y = 0.2461\,x + 0.8161$	0.9822
85	$y = 0.2191\,x + 0.8017$	0.9791
80	$y = 0.1995\,x + 0.7928$	0.9732
75	$y = 0.1832\,x + 0.7809$	0.9775
70	$y = 0.1716\,x + 0.771$	0.9773
50	$y = 0.1331\,x + 0.747$	0.9781

In summary, the minimum required (optimum) ER can be determined from the design number of ESALs and the reliability level. This relation between the optimum ER and the number of ESALs and reliability level was obtained based on the calibration of ER value for an uncracked pavement section with the lowest ER value. For a pavement section, once the reliability and traffic information are obtained, the minimum required ER can be uniquely defined either from Figures 4.6 and 4.7, or from the equations listed in Table 4.3.

5. DEVELOPMENT OF FLORIDA TOP-DOWN CRACKING DESIGN TOOL

5.1 Design Framework

A preliminary framework for cracking evaluation of HMA pavements is presented in Figure 5.1. This figure identifies the major components that were integrated into the top-down cracking model framework. The pavement response and cracking performance were obtained by inputting the materials properties and structural information into the HMA fracture mechanics model. Pavement thickness could be optimized by evaluating the cracking performance. Among all the portions of the framework, the most important one was determination of the material properties used by the model. Depending upon the importance of the project, the material properties are either determined from laboratory tests (e.g., Superpave IDT) or estimated from the volumetric relations.

Specifically, implementation of the framework illustrated in Figure 5.1 follows the procedure described below:

- Laboratory tests (level 1 and 2) or basic volumetric relations that provide the key mixture properties (Superpave IDT fracture parameters) are required to account for the essential factors involved in top-down cracking mechanisms.
- Mixture master curves that efficiently describe the key mixture properties over the required range of temperature and loading times are generated for the evaluation of top-down cracking.
- Pavement response and cracking models that account for thermal and load effects as well as account for the effects of cracks on stress redistributions and temperature gradients, which have been shown to play a significant role in the cracking process.

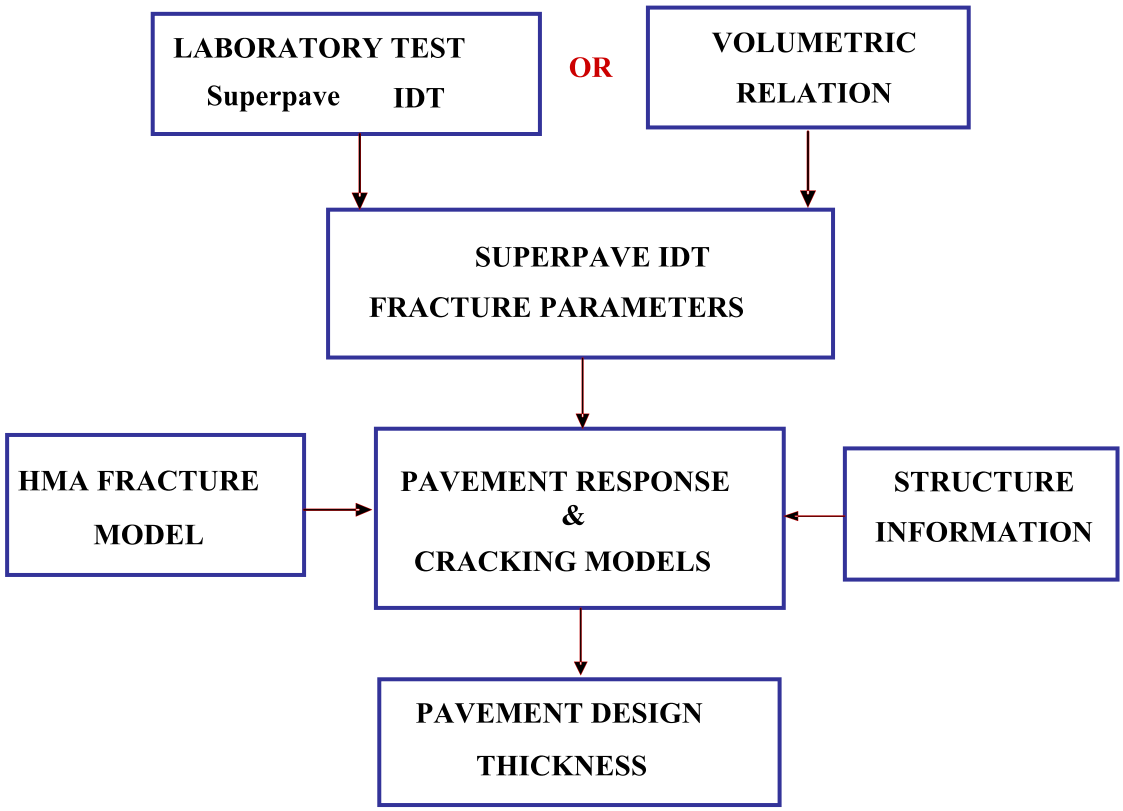


Figure 5.1 Florida framework for cracking evaluation of HMA pavements

- HMA damage and fracture models are used to predict the progression of damage and cracking for a given design condition.
- The pavement thickness design is performed based on the amount of damage at the end of the pavement life and the damage criterion

Obviously, the level of detain and complexity of any one of these components can go from very simple to very complex. The challenge is to make the system as simple as possible without sacrificing the accuracy of the desired outcome.

According to the NCHRP-ME design guide, no laboratory tests need to be performed for Level 3 design. In Florida, the Energy Ratio criterion is used for Level 3 top-down cracking design. The design premise is to ensure a reasonable predicted crack depth after a certain number of years. Based on the ER criterion for top-down cracking, which accounts for the structure and mixture for "averaged" environmental conditions, our design scenario is to determine the asphalt layer thickness for ER ≈ ER $_{optimum}$ at the pavement design life. The Level 3 M-E design flowchart for top-down cracking is shown in Figure 5.2.

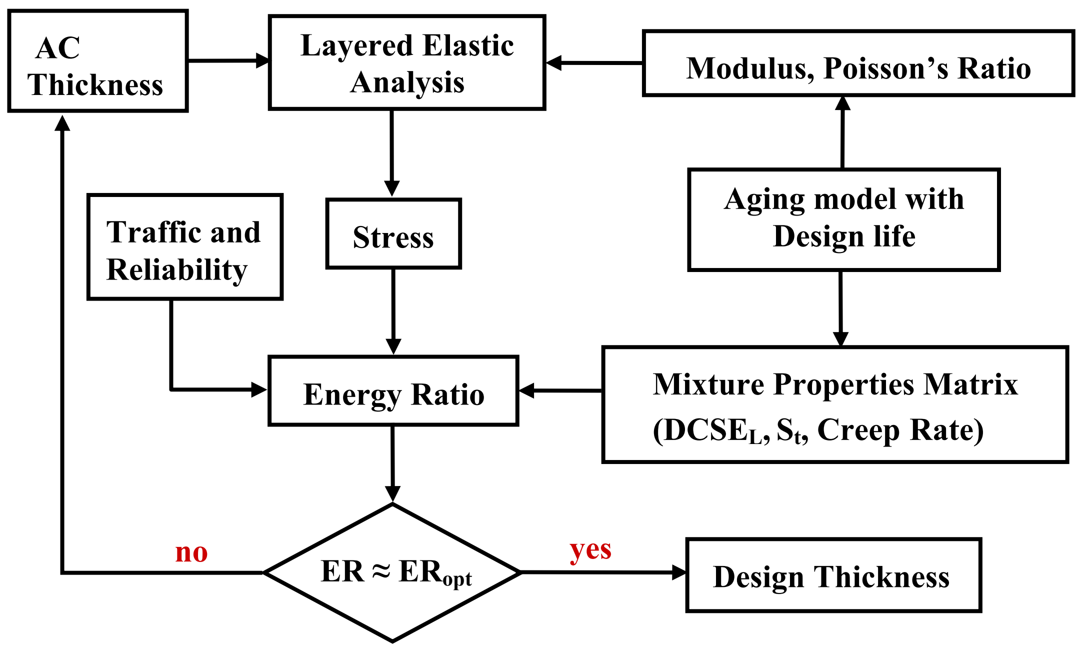


Figure 5.2 Level 3 M-E design flowchart for top-down cracking

According the design flowchart in Figure 5.2, the level 3 design procedures for top-down cracking are given as:

- Assume an initial thickness for the asphalt layer
- The material properties for the asphalt mixture are obtained from volumetric relations developed based on the master curve;
- Input the structural information for the base group and perform linear elastic analysis to obtain the maximum tensile stress in the AC layer;

- Calculate the Energy Ratio using the tensile stress and the IDT fracture parameters of the asphalt mixture at the end of the pavement life;
- Determine the minimum required Energy Ratio from the traffic information and reliability level;
- Check if the calculated ER is approximately equal to the optimum (minimum required) ER:
    - If so, the initial AC thickness is the final design thickness;
    - If not, adjust the AC thickness and repeat the above steps.

5.2 Material Property Models

In Level 3 design, the material properties used to evaluate the top-down cracking performance need to be determined without performing laboratory testing. In Florida cracking model, the mixture properties required in the top-down cracking design procedure include:

- Binder viscosity
- Elastic properties of the mixtures that are need for stress calculation, such as the dynamic modulus |E*| and the Poisson's ratio ν
- The Superpave IDT fracture parameters that are need for calculation of the Energy Ratio:
    - The tensile strength S_t
    - The creep parameters such as D_1 and m-value
    - The dissipated creep strain energy limit ($DCSE_f$)

These mixture properties are estimated from the corresponding material properties models developed by the research team based on the rheological properties and mixture characteristics (gradation and volumetrics). Specifically, the development efforts for the material properties models primarily involved:

- Integration of corrections on the dynamic modulus master curve to predict |E*| for Florida mixtures [12, 13];
- Integrating the global aging model [14] based on binder viscosity and mixture volumetrics to predict the age-hardening effects on mixture properties and corrections thereof.
- Estimation of the creep compliance parameters and the DCSE limit based on the master curve and the aging model.
- Development of a relation between the mixture tensile strength S_t and the mixture stiffness S_{mix} [15].

5.2.1 Dynamic Modulus

The dynamic modulus |*E**| of asphalt concrete is an essential property in analyzing the response of pavement systems. Numerous attempts have been made to develop regression equations to calculate the dynamic modulus from conventional mixture volumetric properties. The predictive equation developed by Witczak and Fonseca [12] is one of the most comprehensive mixture dynamic modulus models available today and has been implemented into NCHRP 1-37A design software. According to Witczak's model, the dynamic modulus $|E^*|$ can be represented by a sigmoidal function as follows:

$$\log\left|E^*\right| = \delta + \frac{\alpha}{1 + \exp\,(\beta + \gamma \log t_r)} \tag{5.1}$$

where

|E*|: the dynamic modulus in compression (in psi);

t_r: reduced time of loading (in seconds) at the reference temperature ($t_r = 1/f$, and f is loading frequency) ;

δ, α : fitting parameters; for a given set of data, δ represents the minimum value |E*|, and $\delta+\alpha$ represents the maximum value of |E*|; δ are α are dependent on aggregate graduation, binder content, and air void content.

β, γ: fitting parameters describing the shape of the sigmoid function (dependent on the viscosity of asphalt binder)

The detailed expressions for δ, α, β, γ are given in terms of the gradation and volumetric properties of the mixture. Based on these expressions, Birgisson et al. [13] obtained a new set of regression constants from extensive complex modulus test data on Florida mixtures. The fitting parameters δ, α, β, γ were expressed as

$$
\begin{aligned}
&\delta = 2.718879 + 0.079524 \times p_{200} - 0.007294 \times (p_{200})^2 + 0.002085 \times \rho_4 \\
&\quad - 0.01293 \times V_a + 0.08541 \frac{V_{be}}{V_{be} + V_a} \\
&\alpha = 3.559267 - 0.005451 \times \rho_4 + 0.020711 \times \rho_{3/8} - 0.000351 \times (\rho_{3/8})^2 \\
&\quad + 0.00532 \times \rho_{3/4} \\
&\beta = -0.513574 - 0.355353 \times \log(\eta_r) \qquad (5.2) \\
&\gamma = 0.37217
\end{aligned}
$$

where

V_a: percent air void content by volume;

V_{be}: effective asphalt content, percent by volume;

$\rho_{3/4}$ ($\rho_{3/8}$, ρ_4): percent weight retained on 19 (9.5, 4.75-mm) sieve;

p_{200}: percent weight passing 0.75-mm sieve;

η_r: binder viscosity at the reference temperature in 10^6 poise.

The constants in (5.2) obtained by Birgisson et al. [13] by nonlinear regression were found to give a better prediction for the dynamic modulus for Florida mixtures. To check the quality of the prediction, some dynamic modulus test data for Florida mixtures were used for comparison. The measured data were obtained at three different temperatures (10 ^{o}C, 25 ^{o}C and 40 ^{o}C) and four different frequencies (1, 4, 10 and 16 Hz). The predicted values for the dynamic modulus of these mixtures from Witczak's equation and from the Florida modified version were compared with the measured data. The comparisons are shown in Figure 5.3 and Figure 5.4, respectively. It can be observed from Figure 5.4 that the modified |E*| predictive equation gives much better prediction.

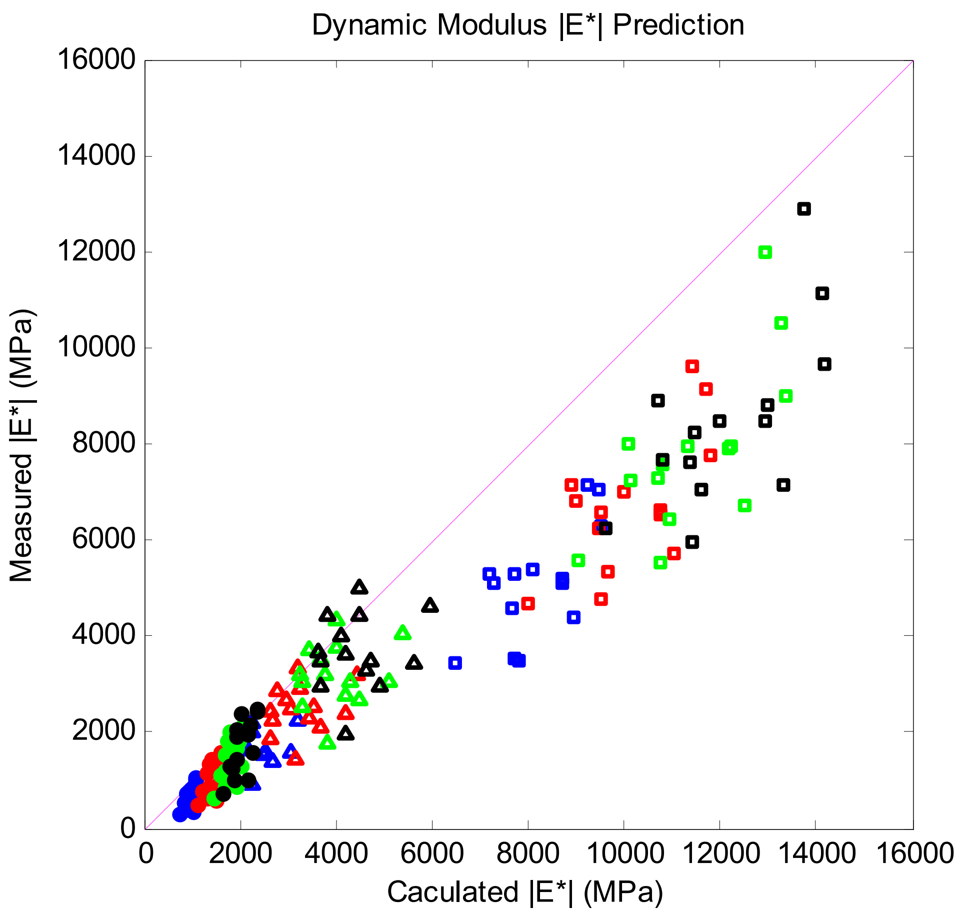


Figure 5.3 Comparison between the measured |E*| data for Florida mixtures and the predicted values from Witczak's equation

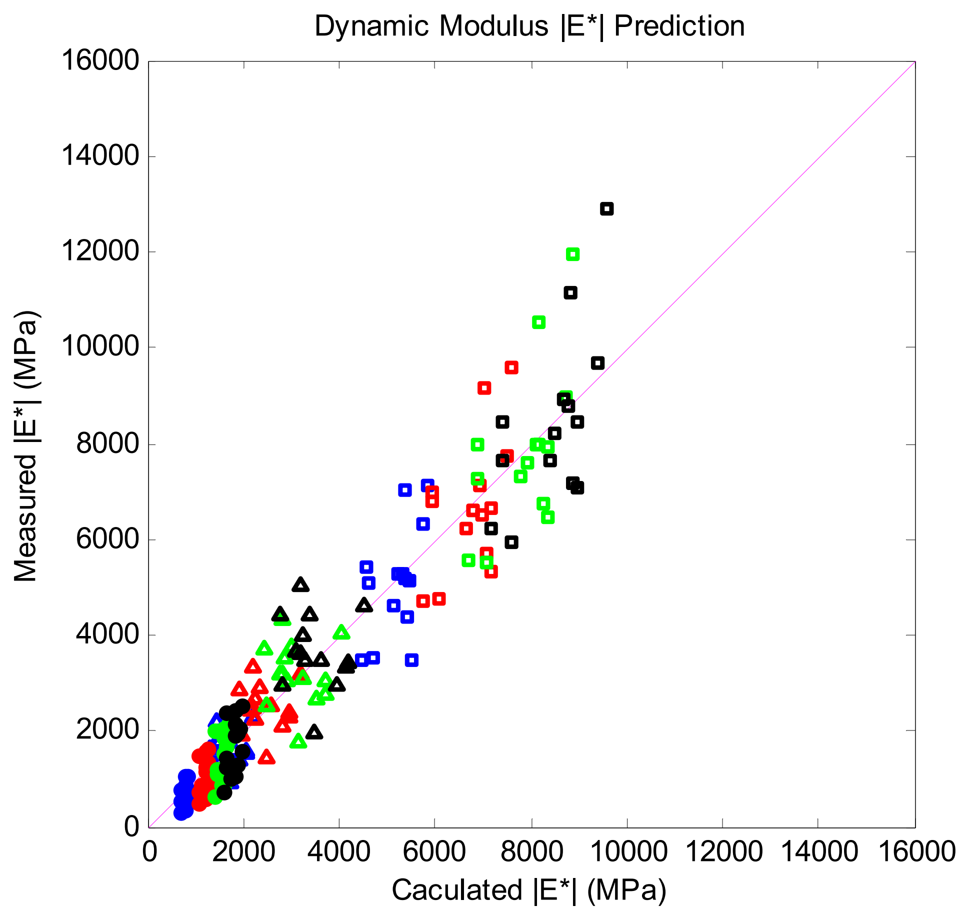


Figure 5.4 Comparison between the measured |E*| data and the predicted values obtained from Florida modified |E*| master curve

5.2.2 Binder Viscosity and Global Aging Model

First, the binder viscosity at mix/laydown condition (t = 0) needs to be determined. For Level 1 and Level 2 design, the following binder test is required:

- Conduct G*-δ on the proposed asphalt binder (AASHTO T315) at ω=1.59 Hz (10 rad/s) over a range of temperatures. For Level 2, the binder viscosity or stiffness can also be estimated using conventional asphalt test data such as Ring and Ball Softening Point, absolute and kinematic viscosities, or using the Brookfield viscometercorrections;
- Develop A-VTS for mix-compaction temperature.

In Level 3 design, the research team suggested to use typical A-VTS values provided in the Design Guide software based on the binder performance grade (PG) to estimate the binder viscosity at mix/laydow condition:

$$\log\log(\eta) = A + VTS \times \log(T_R) \tag{5.3a}$$

where η is the binder viscosity in centipoises (10^{-2} poise), T_R is the temperature in Rankine, and A and VTS are the regression constants. Typical values of A and VTS for three asphalt binders that are commonly used in Florida were given as:

PG 64-22: A = 10.98 VTS = –3.68

PG 67-22: A = 10.6316 VTS = –3.548 (5.3b)

PG 76-22: A = 9.715 VTS = –3.208

The research team suggested that the in-serve viscosity of the asphalt binder be estimated by using the global aging model in the current MEPDG software (developed under NCHRP 1-37A). However, the research team also strongly suggested that a correction to the global aging model be considered to make the model suitable for Florida conditions (see Section 5.2.2.3). The corrected model was integrated into the top-down cracking design tool to take into account the effects of asphalt aging on the mixture properties. The asphalt aging is quantified by the binder viscosity, which is directly related to the prediction of dynamic modulus, as seen from Equation (5.2), and the creep properties, which will discussed in the following sections.

5.2.2.1 Mix/Laydown condition to field aging

For aged conditions (t>0), the viscosity of the asphalt binder at near the pavement surface (depth z = ¼ in or 6.25 mm) could be estimated from the following in-service surface aging model [14]:

$$\log\log(\eta_{aged}) = F_{AV} \times \frac{\log\log(\eta_{t=0}) + A_f\, t}{1 + B_f\, t} \tag{5.4}$$

where t is the time in months, and A_f and B_f are field aging parameters given as

$$A_f = -0.004166 + 1.41213\, C_f + C_f \log(\text{Maat}) + D_f \log\log(\eta_{t=0})$$

$$B_f = 0.197725 + 0.068384 \log C_f$$

$$C_f = 10\text{^}(274.4946 - 193.831 \log T_R + 33.9366 \log^2 T_R)$$

$$D_f = -14.5521 + 10.47662 \log T_R - 1.88161 \log^2 T_R$$

where Maat is the mean annual air temperature in Fahrenheit (^{o}F) .

Equation (5.4) involves an air voids adjustment factor F_v, which can be written as:

$$F_v = \frac{1 + 1.0367 \times 10^{-4} \times VA \times t}{1 + 6.1798 \times 10^{-4} \times t} \tag{5.5}$$

where VA is the air voids expressed in percentage at time t (in months). The predictive equation for the change of air voids with time was suggested as follows:

$$VA = \frac{VA_{orig} + \exp(-1.0528\, t) - 1}{1 + 0.01406t + 0.00125\, t^{0.2307} \times \text{Maat} - 0.00325\, t \times \eta_{orig,77}} \tag{5.6}$$

where VA_{orig} is the initial air voids (in percentage) and $\eta_{orig,\,77}$ is the original binder viscosity at 77^{o}F expressed in Mega-Poise (10^6 Poise).

5.2.2.2 Viscosity-depth relationship

The depth at which the viscosity is evaluated is an important consideration for the long term aging phenomena. This is due to the fact that the viscosity of the asphalt changes with depth at any given time, with the greatest change occurring in the top one inch of the asphalt layer. Review of the factors that have been determined to play an important role in the mechanism of top-down cracking indicated that the stiffness gradient induced by differential aging with depth need to be captured for accurate prediction. The viscosity-depth model available in the current MEPDG software describes the aged viscosity as a function of depth based on the aged viscosity from the surface aging model and the viscosity at mix/laydown condition. The model suggests the following viscosity-depth relation:

$$\eta_{t,z} = \frac{\eta_t (4+\chi) - \chi \cdot (\eta_{t=0})\,(1-4z)}{4(1+\chi \cdot z)} \tag{5.7}$$

and

$$\chi = 23.82\exp(-0.0308 \cdot \text{Maat})$$

where z is the depth (in inch) and

$\eta_{t,z}$ = aged viscosity at time t and depth z (in Mega Poise)
$\eta_{t,}$ = aged surface viscosity (Mpoise)
Maat = the mean annual air temperature in Fahrenheit

It is observed from Equation (5.7) that the following conditions are satisfied:

$$\eta_{t,z}\Big|_{z=0.25} = \eta_t \quad \text{and} \quad \eta_{t,z}\Big|_{t=0} = \eta_{t=0} = \eta_0$$

The average viscosity of the binder over the depth (h_1, h_2) can obtained as

$$\bar{\eta} = \frac{\int_{h_1}^{h_2} \eta_{t,z}\,dz}{h_2 - h_1} = \eta_0 + \frac{(\eta_t - \eta_0)(4+\chi)}{4+\chi(h_2 - h_1)} \ln\frac{1+\chi h_2}{1+\chi h_2} \tag{5.8}$$

Figures 5.5 and 5.6 plot the variation of binder viscosity with time and depth predicted from the aging model. It is observed from these figures that the binder ages a lot faster at the surface of the AC layer and that aging mostly occurs during the first a couple of years after the pavement is constructed.

5.2.2.3 Correction of the aging model by field calibration

The research team has found that the aging model described above overestimates the aging of mixture in Florida based on their field measurements on 12 Superpave sections, which

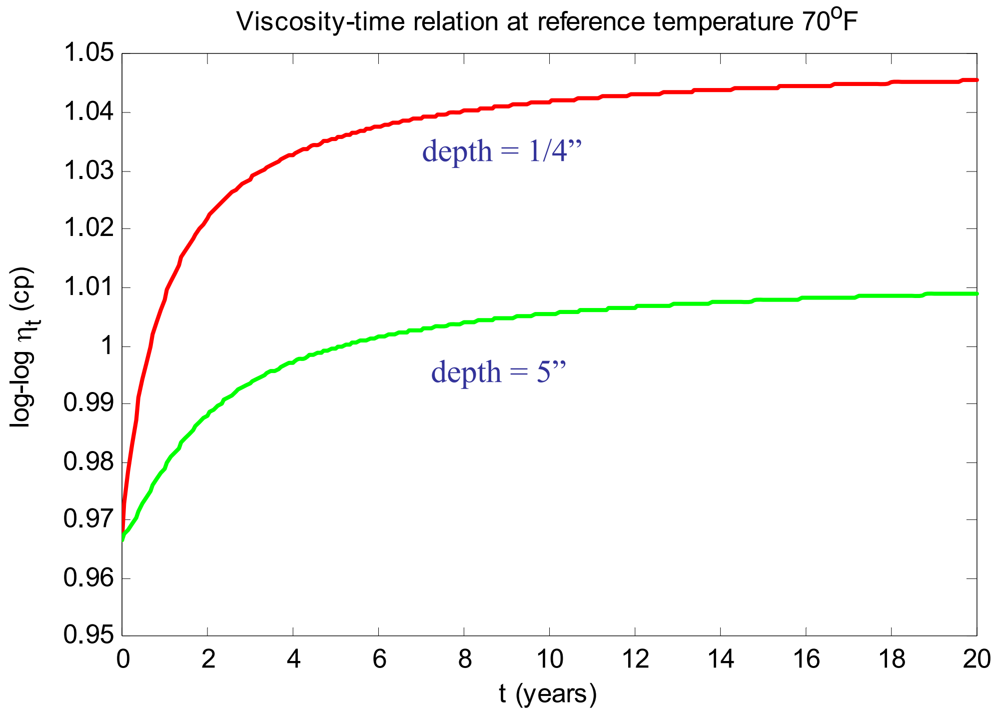


Figure 5.5 Variation of the binder viscosity with time predicted from the aging model for two different depths

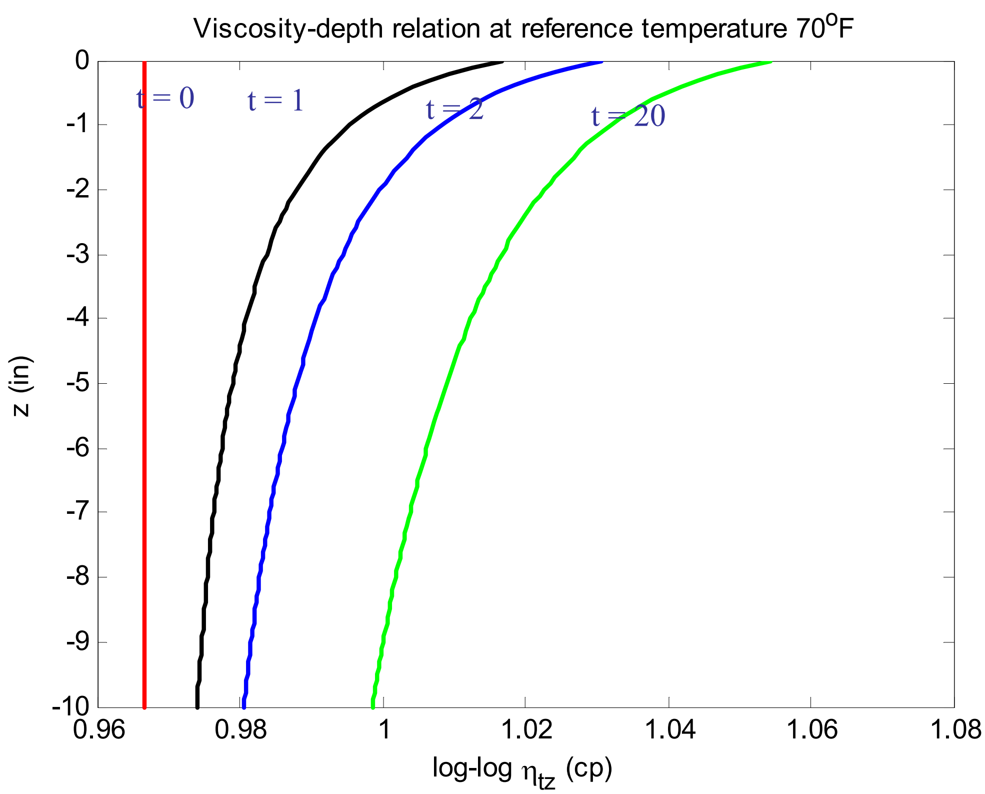


Figure 5.6 Variation of the binder viscosity with depth predicted from viscosity-depth relation at different time t (years)

was part of the Superpave Monitoring project. These measured viscosity data were used to calibrate the aging model to make it suitable for Florida. In the first two years after construction, field cores were extracted at the end of each year and the binder viscosity was measured for two different depths at two different temperatures: 25°C and 60°C. The viscosity at 60°C was measured by using DSR test and that at 25°C measured by penetration test. As an illustration, Figure 5.7 and Figure 5.8 show some of the comparisons between the measurements and the predicted values using the above aging model (denoted as "uncorrected" in the figures) at 60°C and 25°C, respectively. In these figures, Layer A and Layer B represent the surface AC layer

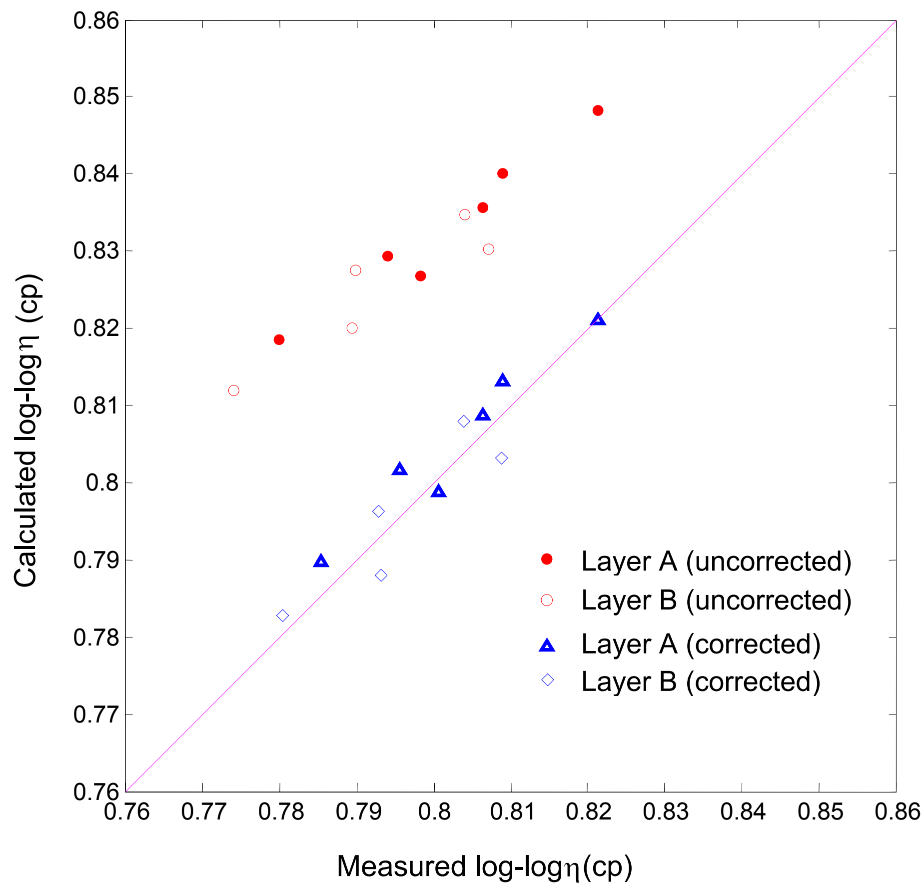


Figure 5.7 Measured values of binder viscosity at 60°C versus the values predicted from the aging model at two years after construction

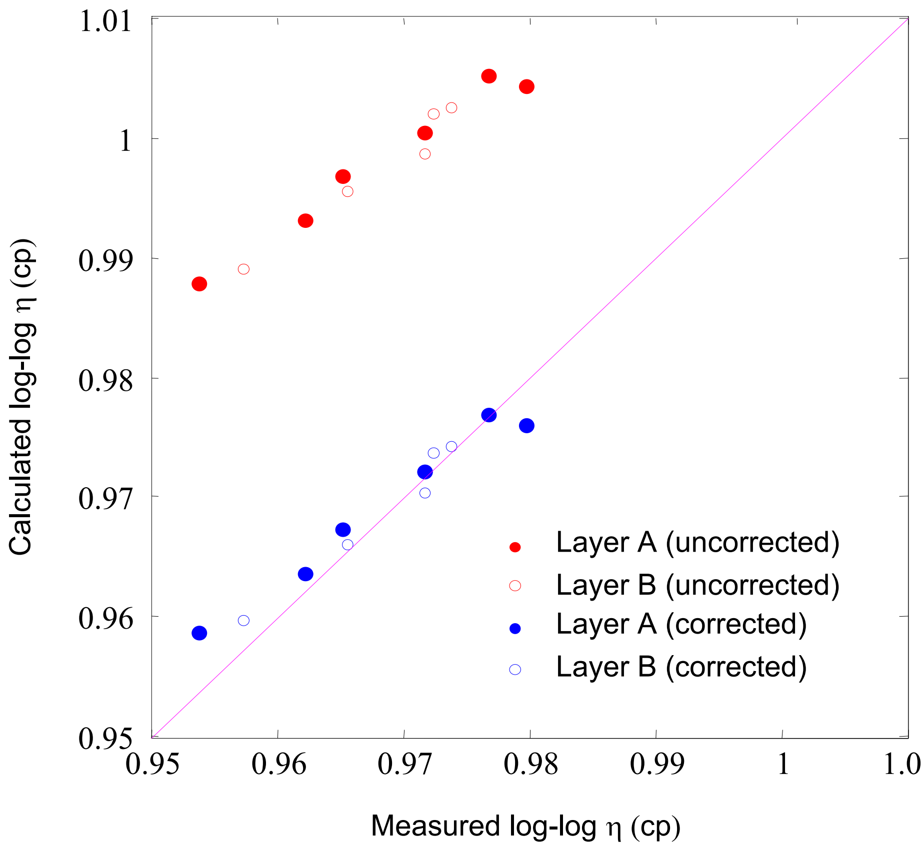


Figure 5.8 Measured values of binder viscosity at 25°C versus the values predicted from the aging model at two years after construction

and the layer below the surface AC in field. It is observed from these figures that the global aging model in the current MEPDG software presents a significant overprediction of the binder aging. The research team proposed a simple empirical correction on the current aging model by introducing a reduction factor F_r:

$$\log\log(\eta'_{aged}) = F_r \times \log\log(\eta_{aged}) \quad \text{and} \quad F_r = 1 - \frac{c_r}{\pi}\arctan(t_y) \tag{5.9}$$

where η'_{aged} is the corrected viscosity, t_y is the time in years, and c_r is a constant between 0.06 and 0.1 (we take $c_r = 0.08$). After correction, the predicted values (denoted as "corrected" in Figures 5.7 and 5.8) agreed well with the measured.

5.2.3 Tensile Strength

In the evaluation of the cracking performance of asphalt mixture, the tensile strength is an important factor that needs to be estimated. In their work on evaluation of the mix low temperature cracking performance, Deme and Young [15] discovered that the tensile strength of mix is well correlated with the mixture stiffness at a loading time t = 30 minutes. They had extensive data measurements in the temperature range of –40 to 25°C. Their data were digitized and plotted in Figure 5.9 (denoted as "o"). Based on these data, the research team proposed the following relation between the mix stiffness and the tensile strength using nonlinear regression:

$$S_t = \sum_{n=0}^{5} a_n \left(\log S_f\right)^n \tag{5.10a}$$

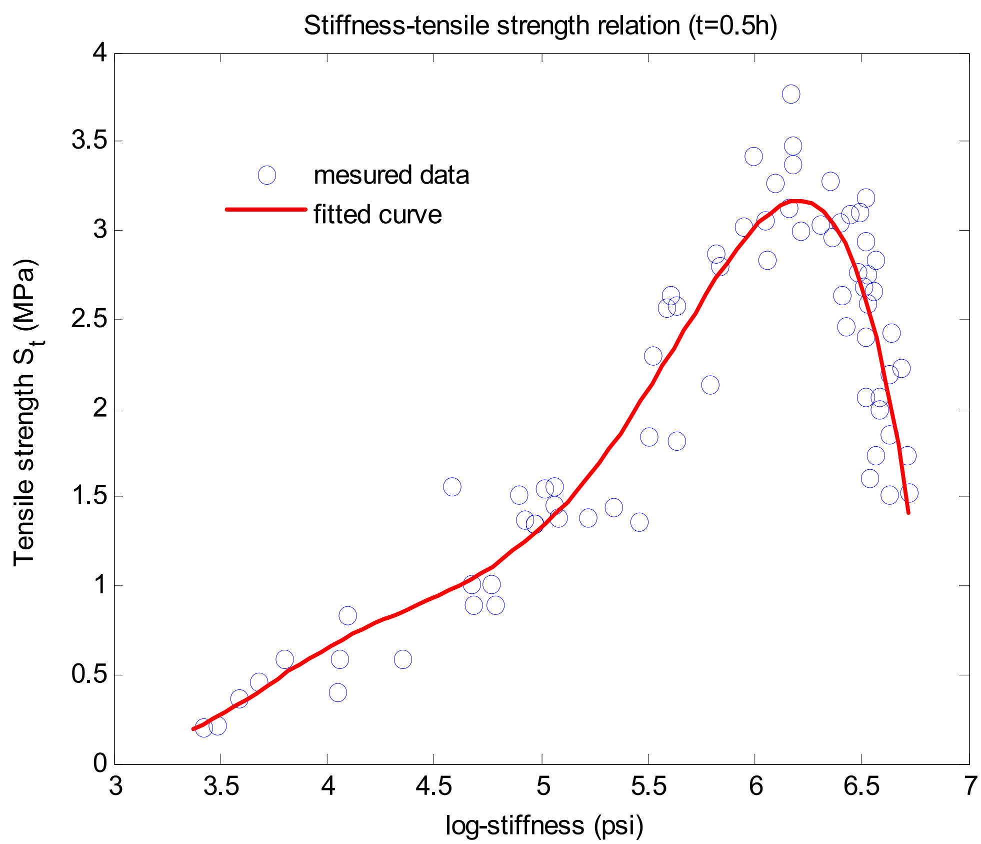


Figure 5.9 Relation between mix stiffness and tensile strength (the measured stiffness data, denoted as "o", were obtained at t = 1800s)

where S_t is the tensile strength (in MPa), and S_f is the tensile stiffness (in psi) that can be obtained from the dynamic modulus by introducing a reduction factor λ_r: $S_t = \lambda_r \times |E^*|$. The $|E^*|$ is estimated from (5.1) and (5.2) by taking t = 1800s and the reduction factor is chosen between 0.3 and 0.5 (the research team suggested $\lambda_r = 0.4$). The constants a_n in (5.10) were given as follows

$$\begin{aligned} &a_0 = 284.01, \quad a_1 = -330.02, \quad a_2 = 151.02, \quad a_3 = -34.03, \\ &a_4 = 3.7786, \quad a_5 = -0.1652 \end{aligned} \tag{5.10b}$$

The fitted curve was also plotted in Figure 5.9. Equation (5.10) was found to give a reasonable prediction for the tensile strength of asphalt mixture.

5.2.4 Creep Compliance Parameters and DCSE Limit

There is no existing model to predict damage and fracture properties, and there is no existing model to predict the changes in these properties induced by aging. However, development, calibration, and validation of a mixture model to predict damage, healing, and fracture properties is clearly a major research effort in its own right, and well beyond the scope of the current research project. The research team had been working to identify rudimentary relationships that could be used for this purpose for cases when measured properties would be obtained. This would involve the use of correlations to predict damage and fracture properties from rheological properties and mixture characteristics (gradation and volumetrics).

5.2.4.1 Creep compliance parameters

Creep compliance is a fundamental property that describes the relation between the time dependent strain and applied stress in viscoelastic materials. Accurate determination and representation of the creep compliance of asphalt mixture is essential to evaluate the cracking performance of asphalt pavements. As seen from the ER formulation described earlier, the ER value strongly depends on the creep compliance parameters D_1 and m. Figure 5.10 gives an illustration of the creep compliance function D(t) and the corresponding creep parameters.

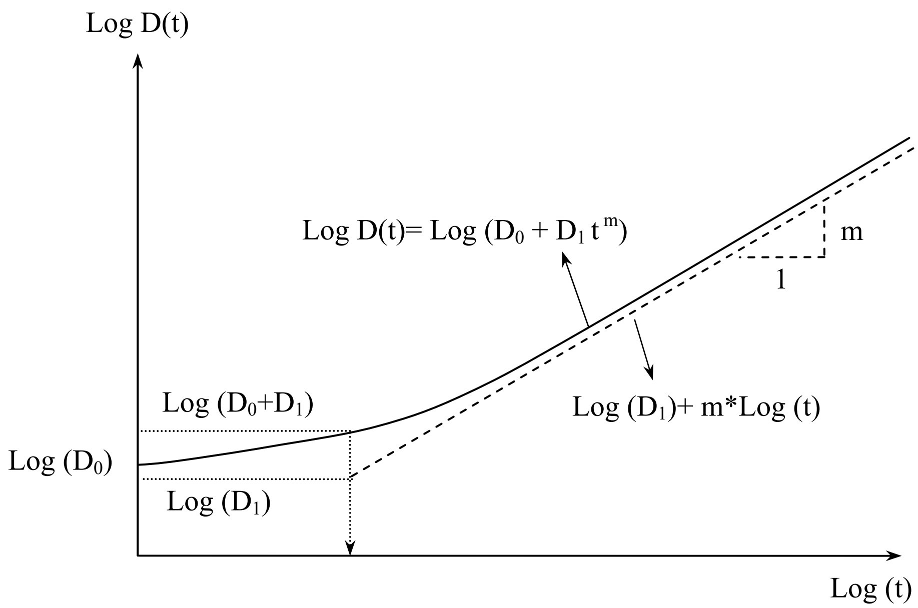


Figure 5.10 Creep compliance function and D(t) and the creep parameters

It is not trivial to estimate the creep parameters D_1 and m. One way is to use the inter-conversion between the dynamic modulus E* and creep compliance D(t). The research team did not use this approach not only because it is complicated but also because the measurements for E* at low frequencies are usually unreliable. It is known that the dynamic modulus E* and the dynamic compliance D* satisfy the relation: $|D^*| = 1/|E^*|$. However, the dynamic compliance $|D^*|$ is not directly related the creep compliance D(t). Based on some lab measurements on the dynamic modulus and creep compliance of the same group of mixtures at different frequencies, the research team found that the magnitude of the dynamic modulus $|E^*|$ and the creep compliance satisfies a hyperbolic transformation, as observed from Figure 5.11. For simplicity, however, the research team assumed that $D(t)=1/|E^*|$ at small times and developed some rudimentary relations based on this relation to estimate the creep compliance parameters from the binder rheological properties and mixture characteristics.

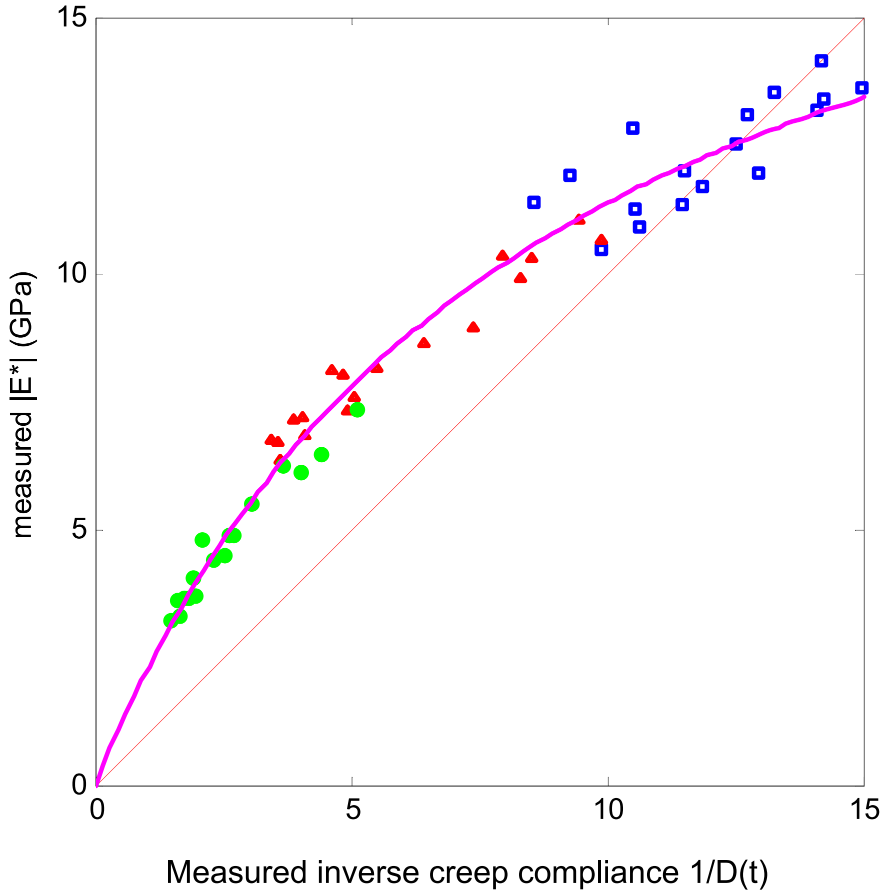


Figure 5.11 Lab measurements of the dynamic modulus and creep compliance

Finally, the research team came up with several empirical equations to estimate the parameters in the tensile creep compliance function expressed in power-law form: $D(t) = D_0 + D_1 t^m$. The D_0 and D_1 can be obtained from the asymptotic values of $\lambda_r |E^*|$ as follows:

$$\log(D_0) = -\delta - \alpha - \log\lambda_r, \quad \log(D_0 + D_1) = -\delta - \frac{\alpha}{1+e^{\beta}} - \log\lambda_r \tag{5.11}$$

where λ_r is the tensile stiffness reduction factor as introduced in (5.10); the parameters δ, α, and β can be obtained from the mixture volumetrics and binder viscosity using Equation (5.2). The m-value was obtained by taking the derivative of the master curve equation (5.1) with suitable modification. The research team used the the slope of log t – log $|E^*|$ curve at t = 1000 s (denoted as m_0) as a base value:

$$m_0 = \alpha\gamma \times \frac{\exp(\beta + 3\gamma)}{[\,1 + \exp(\beta + 3\gamma)\,]^2} \tag{5.12a}$$

After incorporating an additional term that takes into account the viscosity change due to aging effects, the final predictive equation of m-value was given as:

$$m = m_0 + \frac{\kappa}{\log\log\eta} \tag{5.12b}$$

where κ is a constant (suggested value is $\kappa = 0.408$) and η is the binder viscosity in Mega Poise.

5.2.4.2 Dissipated creep strain energy limit

The dissipated creep strain energy limit (or DCSE to failure) has been correlated to the resistance to top-down cracking in field [7, 9, 10]. Estimation of $DCSE_f$ was found to be extremely difficult, especially its change induced by aging. It is generally believed that the $DCSE_f$ is related to the strain rate of the asphalt mixture $\dot{\varepsilon}_{mix}$, which is inversely proportional to the mix viscosity, the tensile strength S_t, and the resilient modulus M_R, as can be observed from Figure 5.12.

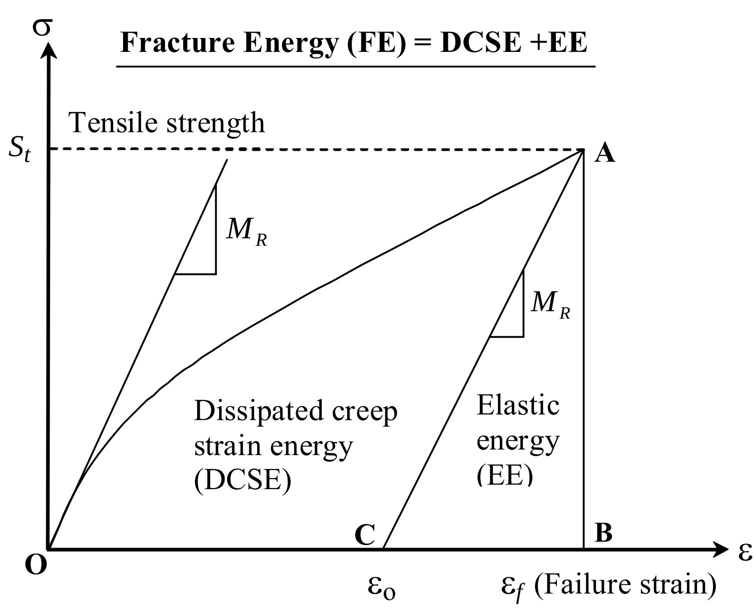


Figure 5.12 The fracture energy (FE) and dissipated creep strain energy (DCSE)

Based on their experience, the research team believed that it was reasonable to express the $DCSE_f$ as a function of $\dot{\varepsilon}_{mix}$ at t = 1000s, the tensile strength, and the creep parameters. As a result, the following relation was proposed:

$$DCSE_f = c_f \times S_t \frac{m\, D_1}{10^{3(1-m)}} \tag{5.13}$$

where c_f is a function of binder viscosity. For simplicity, it was suggested to take $c_f = 6.9\times10^7$ in the current Level 3 design. It was recognized by the research team that Equation (5.13) was a crude relation for $DCSE_f$. Development of more accurate prediction for $DCSE_f$ is in progress.

Based on the material models presented above, the research team calculated the energy ratio (ER) for the 22 sections illustrated in Figure 4.5. The predicted ER results were plotted in Figure 5.13 against the measured ER values, which are obtained based on the measured mixture properties. It was found the system gave a pretty reasonable prediction on the relative cracking performance of the asphalt pavements. As shown in Figure 5.13, except for a couple of outliers, the predictive system distinguished the cracked from the uncracked pavements, i.e., the cracked pavements are predicted as cracked, and uncracked predicted as uncracked, although the ER values did not agree very well with the measured ones.

5.3 Rehabilitated Pavement Design

The design framework for the rehabilitated pavement (overlay) design is the same as that for the new pavement design. The material fracture properties (IDT test parameters, including creep rate, tensile strength, and $DCSE_L$, etc.) used to calculate the energy ratio of the system are determined from the AC Overlay, as the resistance to top-down cracking is mainly provided by the surface layer. Determination of the properties for the AC overlay design is the same as for the new pavement design, which has been described thoroughly in Section 5.2.

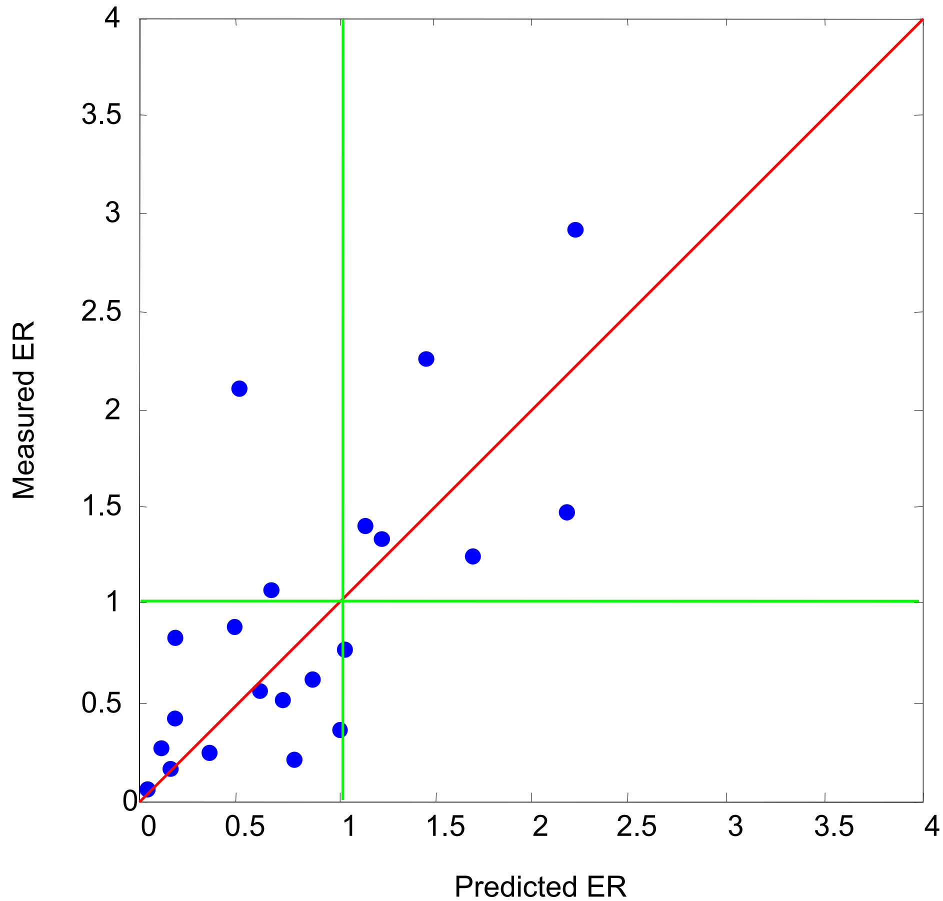


Figure 5.13 The predicted ER versus the measured ER

To take into account the structural effect of the existing AC layer in the overlay design, it was suggested that the entire AC layer (overlay + existing AC) be used to calculate the tensile stress involved in the energy ratio formula. For this purpose, the equivalent AC layer as illustrated in Figure 5.14 is used to represent the top two layers, including the AC overlay and existing AC layer. It is worth mentioning that the effective existing AC layer should exclude the milled part. The properties of the equivalent AC layer are taken as the same as the new AC overlay. As a result, the existing AC layer is transformed to a layer of the same properties of the overlay and with a thickness of h_{eq}, which is determined from the formula shown in Figure 5.14. The thickness of the equivalent AC layer is equal to h_{OL} + heq. The subsequent analysis follows the same procedure as the new pavement design.

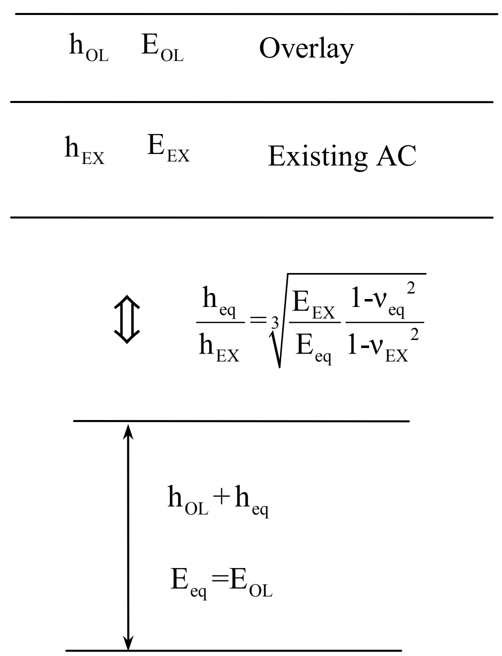


Figure 5.14 Use of an equivalent AC layer in the overlay design

The research team would like to mention that the stress used to calculate the energy ratio for a rehabilitated system is the tensile stress at the bottom of the equivalent AC layer. The elastic properties of the existing AC layer are estimated based on the pavement conditions (good, fair, or poor) determined by the pavement design engineers according to the Florida Pavement Design Guide [16].

6. Windows-Based Design Software

The mixture properties sub-models were integrated with the Florida cracking model, which resulted in a calibrated and validated model for predicting top-down cracking in HMA layers. An interactive Windows-based mechanistic-empirical (M-E) pavement design tool was developed based on this model. This design tool can be used for new pavement design as well as for pavement rehabilitation. The design tool was fully integrated with key mixture cracking properties and was capable of doing pavement life prediction for new, existing, and rehabilitated asphalt pavements.

This section gives a brief description of the key components of the software developed by the research team. Details and instructions on how to use the software are provided in the User's Manual (see Appendix).

6.1 New Pavement Design

The design studio for new pavements includes two major modules: the input and output modules. The structures and key components of these modules are illustrated in Figure 6.1.

New Pavement Design Studio

Input Module

- Traffic
- Reliability
- Climatic Information
- Top Structure (AC) Layer
- Base Group

Output Module

- ER value
- Optimum thickness
- Optimization curve
- ER-pavement life curve

Figure 6.1 Input and output structure for the new pavement design studio

A simple demonstration of the input and output for new pavement design is given below.

6.1.1 Input Module

The input module includes the following basic input menus: traffic, reliability, climatic information, AC layer information, and the structural information for the base and stabilized subgrade. For simplicity, screenshots were only given for some of the input menus. More details can be found in the User's Manual.

6.1.1.1 Traffic input

In the Level 3 analysis, the traffic input is quite simple, as illustrated in Figure 6.2. The user only needs to input the total design number of ESALs (Equivalent Single Axle Loads) or select a FDOT traffic level, specify the pavement design life and the traffic growth rate. The traffic load can be either set as standard ESAL (9000 lb and 100 psi) or user defined.

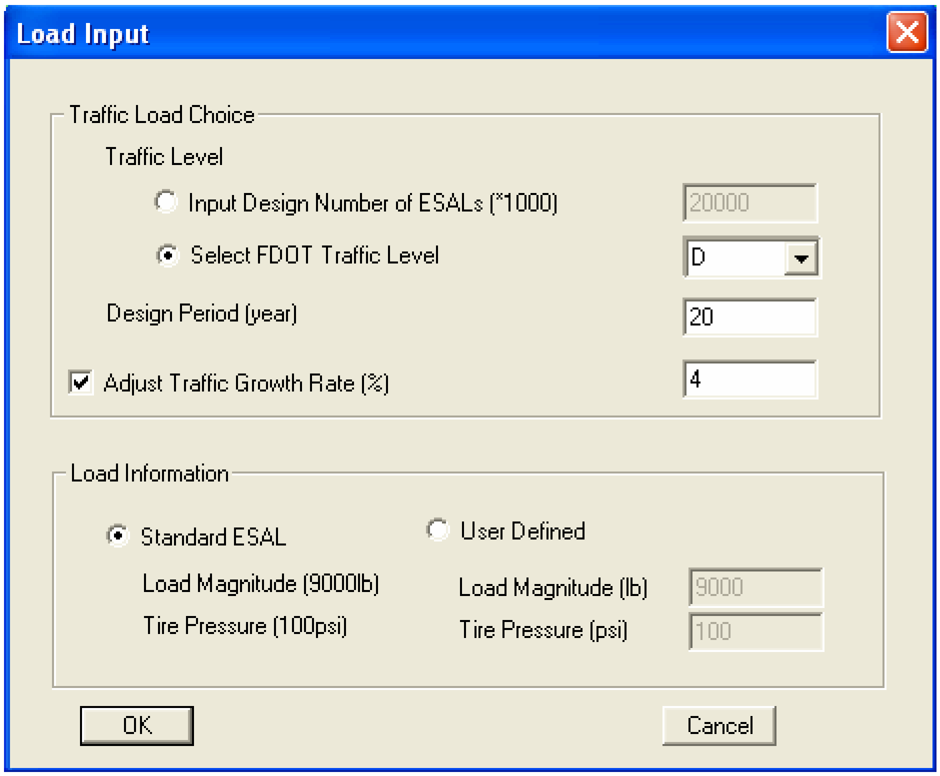


Figure 6.2 Traffic information input

6.1.1.2 Reliability input

The FDOT specifies different reliabilities for different roadway facilities for new pavements and rehabilitation (for example, for new pavements, 80-95% for limited access, 80-90% for urban arterials, 75-90% for rural arterials, etc.) [16]. The designer has the flexibility in selecting the values that best fits the project when choosing the reliability. The reliability together with the traffic information will be used to determine the minimum ER required for the pavement, as described in Section 4.3. For example, if total design number of ESALs is 20 million and the reliability is 95%, the minimum required ER is approximately 1.45, which can be calculated from the second equation in Table 4.3. There are built-in functions to calculate the minimum required ER and no addition inputs are required.

6.1.1.3 Climatic information

In the climatic information input, the designer only needs to select the nearest locations to the project. The current model only takes the MAAT of the selected location as input, which will be used to estimate the aging effect.

6.1.1.4 Top structure layer (AC)

The AC layer design includes mix selection and design, binder selection, and determination of the basic fracture properties of the mixture. The input interface for AC layer includes 3 tabs, as shown in Figure 6.3. First, the designer needs to select 4 basic mix types (SP9.5 and SP12.5 coarse/fine mixtures) specified by FDOT. For each mix, there is a default gradation, which was suggested by the research team based on their work and experience on graduation. The designer can also make adjustment to the graduation by changing the percent passing of several key sieve sizes (see Figure 6.3). The designer also needs to input an estimated design thickness (default value is 4") and air voids in compacted field mix (default value is 6%). The estimated design thickness will be updated automatically in the optimization process. For each mix type provided, there is a suggested VMA value, which can be adjusted by the design engineer.

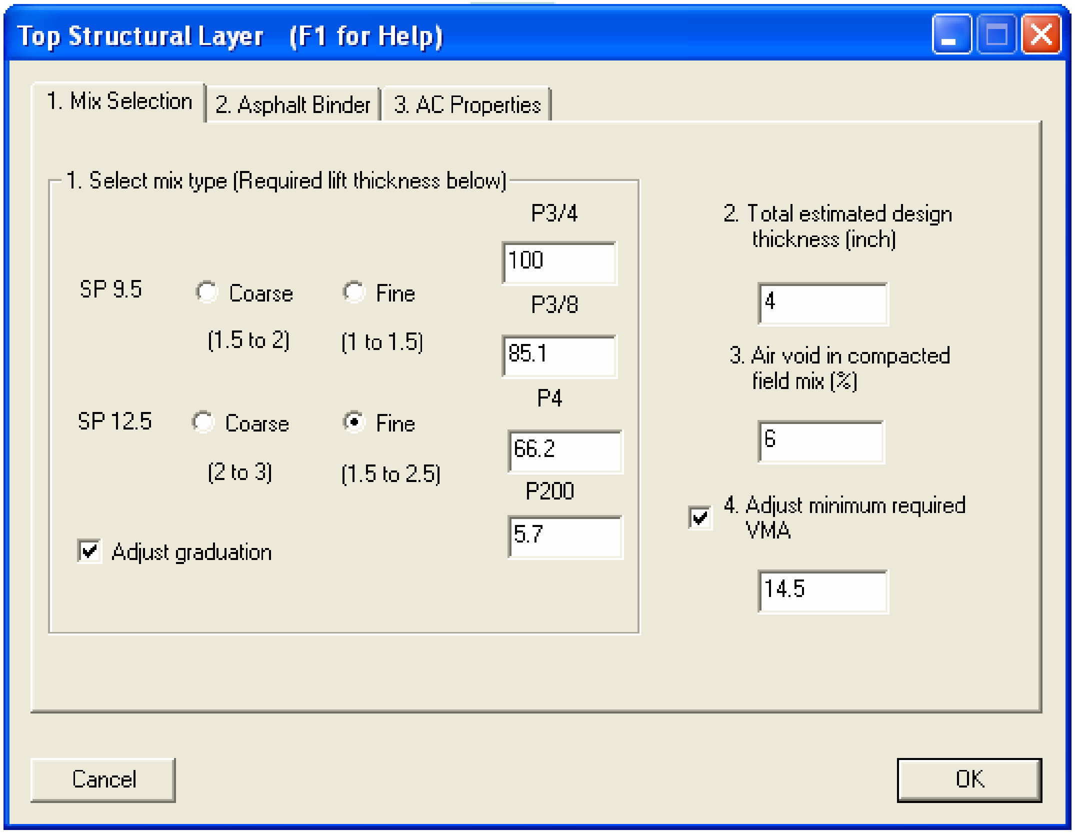


Figure 6.3 Input of the AC layer information: mix selection

In the next step (Tab 2 in Figure 6.3), a selection of asphalt binder performance grade (PG 64-22, 67-22, or 76-22) needs to be made. Based on this selection, the binder viscosity at mix/laydown condition is calculated by using the A-VTS relation expressed in (5.3). The temperature in (5.3) was set at 50°F (10°C), which is believed to be representative of the intermediate in-service temperatures associated with conditions that are conducive to top-down cracking [7].

After inputting the mix and binder information, the mixture properties (including $|E^*|$, ν, D_1, m, S_t, $DCSE_f$) will be generated from the material models described in Section 5.2. These values will be set as the default values (at t = 0) and listed in Tab 3, as illustrated in Figure 6.4. In the design process, these values will be automatically updated at each time point (in months)

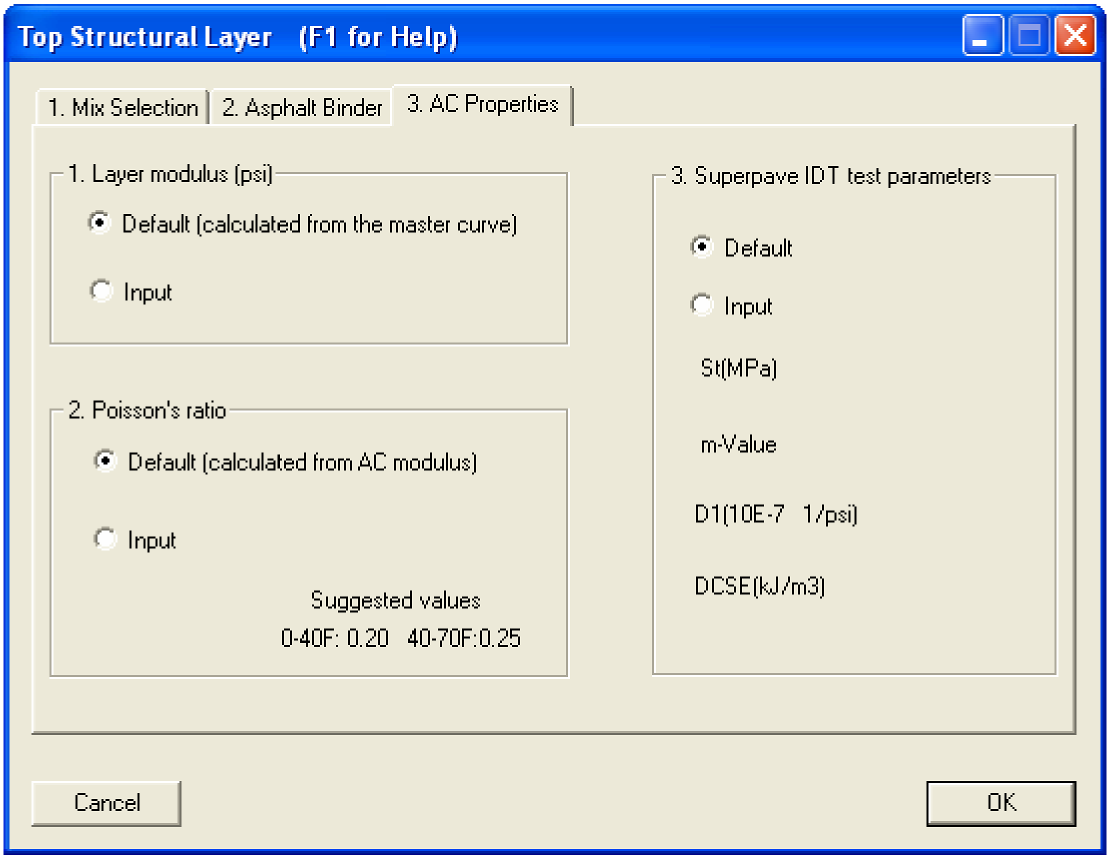


Figure 6.4 Input of the AC layer information: AC properties

of the pavement life. It is worth mentioning that the user can also input the material properties directly by checking the "Input" button in Tab 3, if the corresponding measurements are available, to evaluate the cracking performance of an existing pavement. In this case, the inputs in Tab 2 are not necessary.

6.1.1.5 Structural information of the base group

Finally, the information for the base and stabilized subgrade need to be inputted to evaluate structural effects. The structural information of the base group is for calculation of the stresses in the AC layer. As shown in Figure 6.5, the designer can select the number of layers and the materials used for each layer. FDOT has some recommendations for the base group materials (such as, granular base, graded aggregate, asphalt base, etc.) and the properties of these materials [16]. The material type and properties can also be user defined. Other information such as the layer thicknesses and interface conditions is shown clearly in Figure 6.5.

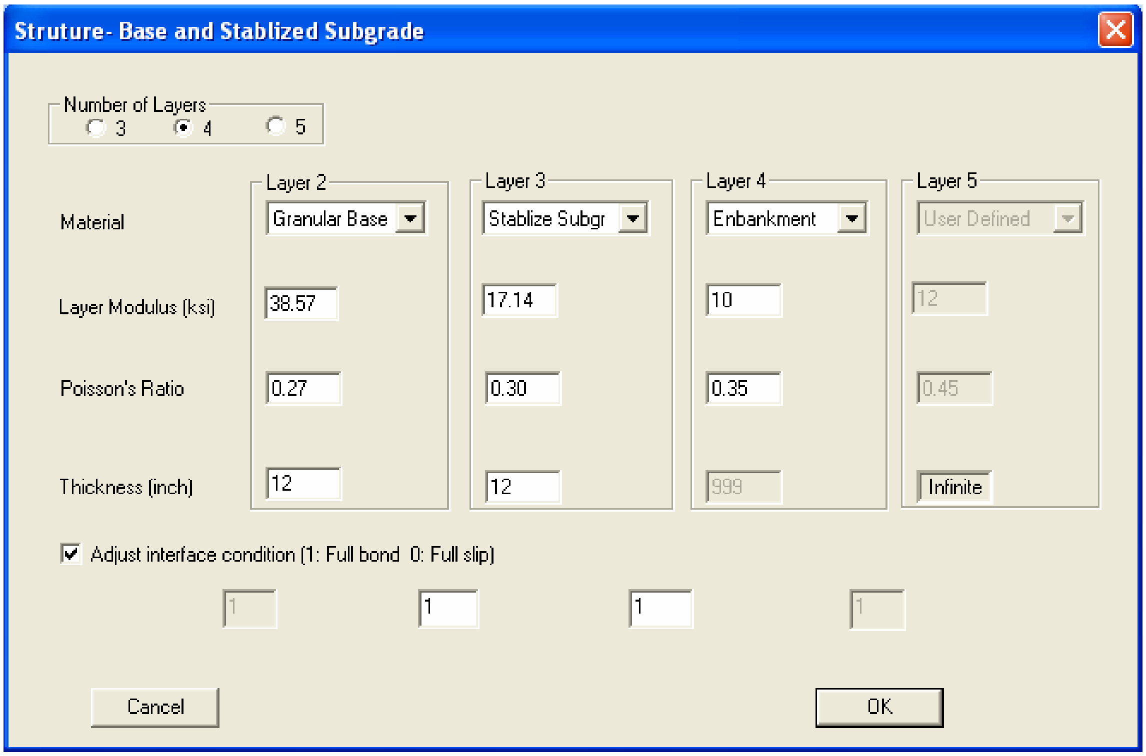


Figure 6.5 Structural information for base and stabilized subgrade

6.1.2 Output Module

There is one main interface in the output menu, as illustration in Figure 6.6. The program first outputs the calculated ER based on the input information and the maximum tensile stress at the bottom of the AC layer (which was used to calculate the ER value). The ER value shown in the “Calculated ER” field was obtained at the end of the pavement design life. The user needs compare this ER value with the minimum required ER value shown in the “Optimum ER” field. If the calculated ER is not approximately equal the optimum ER, the user can optimize the AC thickness by clicking the “optimize” button (see Figure 6.6). As a result, an ER-thickness curve

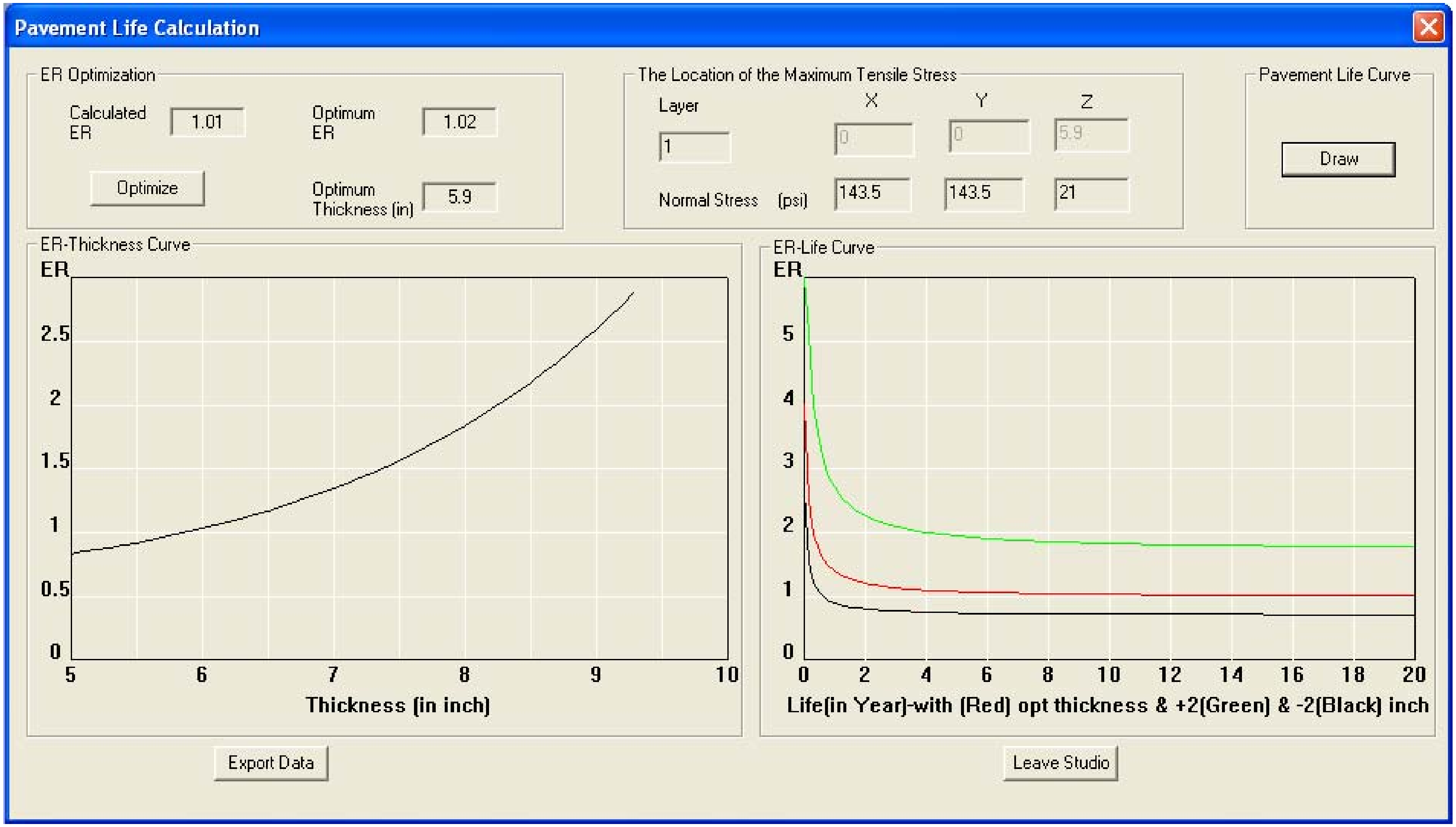


Figure 6.6 Output: AC thickness optimization (left figure) and ER-pavement life curve (right figure)

will be plotted. Based on this curve, the design tool searches for the optimum thickness that gives the ER value equal to the minimum required ER. The optimum AC thickness is then shown in the "Optimum Thickness" field. The optimization curve also shows the sensitivity of the ER value to the AC thickness, which will guide the design engineer in selection of the optimum thickness value.

In addition, the design tool provides the option of drawing the ER-pavement life curves, i.e., the design tool calculates the ER values from the beginning to the end of the pavement life for different pavement thickness. In the right graph of Figure 6.6, three ER-pavement life curves for different AC thicknesses (including the optimum thickness h_{opt} and h_{opt} plus/minus 2 in) are plotted. These curves show that the ER value drops down significantly as the pavement ages. The sensitivity of the ER value to the pavement thickness can also be observed from these curves. One can see that the pavement resistance to top-down cracking increase as the pavement thickness increase, which is consistent with the observation in another work by the research team [8].

6.2 Overlay Design

As mentioned in Section 5.3, the overlay design follows exactly the same procedure as the new pavement design. The input and output structure of the overlay pavement design is shown in Figure 6.7. The components of the output module for the overlay design are the same as for the new pavement design shown in Figure 6.1. As for the input module the only difference between the new design and overlay design lies in the AC layer information input. As illustrated in Figure 6.7, the top structure input involves both the overlay and existing AC layer. The overlay part is the same as the AC layer in the new pavement design. The existing AC layer contributes to the structural effects but not directly to the cracking resistance, which is believed to be controlled by the properties of mixtures in the overlay. In the following, only the input for the top structure (AC layer) in the overlay design will be demonstrated.

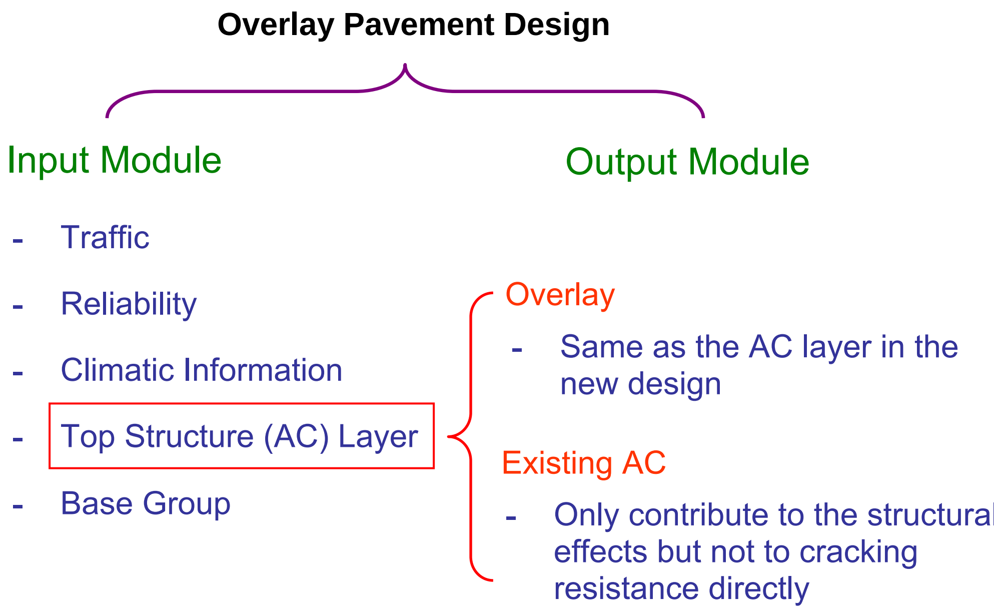


Figure 6.7 Input and output structure for the overlay pavement design

The input menu for the AC layer information in the overlay pavement includes two input tabs: AC overlay (Tab 1) and Existing AC layer (Tab 2), as shown in Figure 6.8 and 6.9, respectively.

It is seen from Figure 6.8 that the AC overlay part also includes mix selection and design, binder selection, and mixture properties. The only difference from the new pavement design is estimated AC layer thickness only include overlay thickness.

For the existing AC layer, the design engineer needs to determine first how many layers will be used to represent the structure. Then, the designer will need to select the material type, thickness, and condition for each layer, as shown in Figure 6.9. Based on the condition of each layer, the user then needs to determine if it is necessary to mill the surface. If milling is necessary, the user will have to input the milling depth. As a result, the effective thickness of the existing layer will be the total thickness minus the milling depth. The design method was

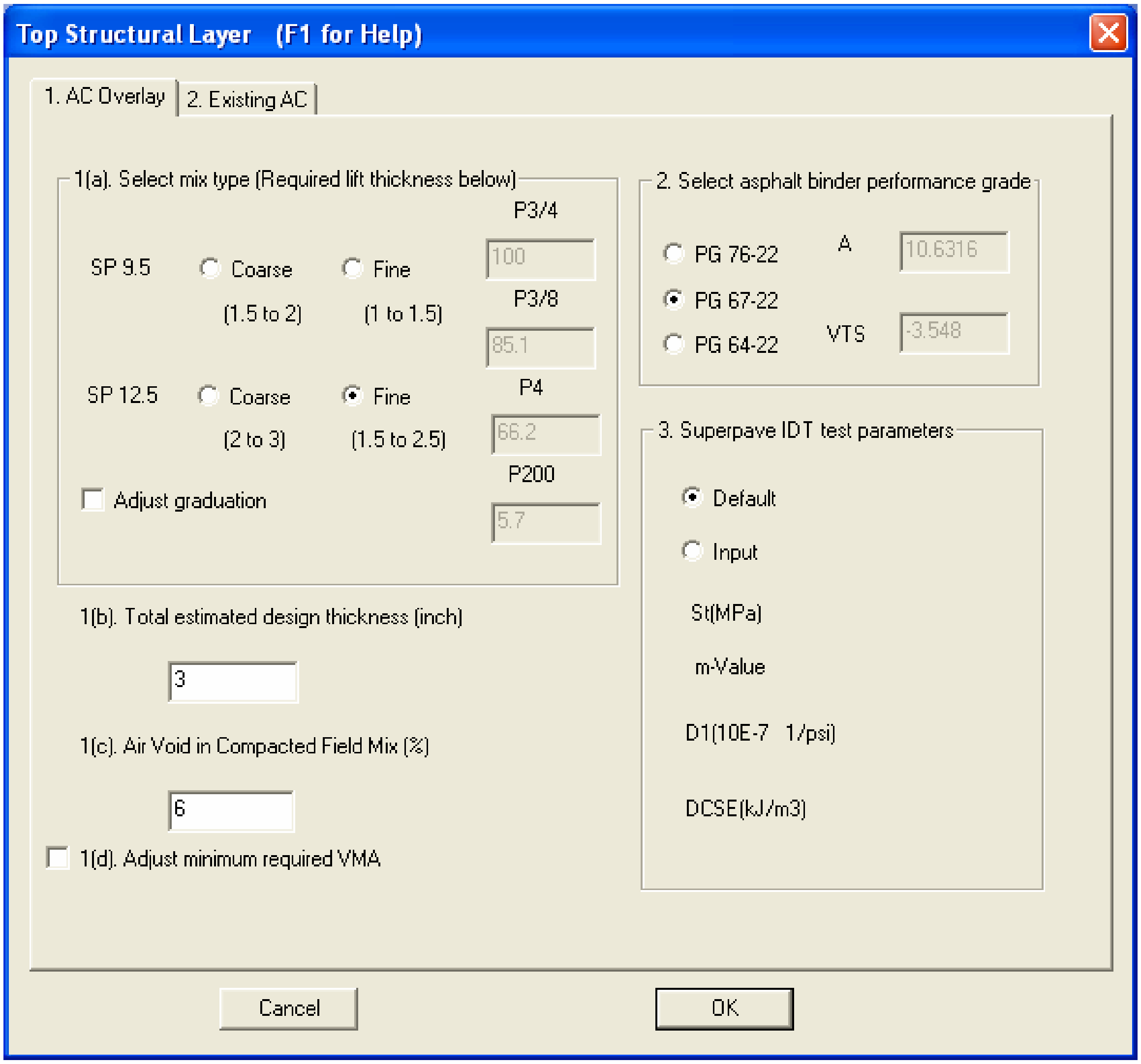


Figure 6.8 Input of the AC layer information: AC overlay

explained in Section 5.3. Excluding the milled layer(s), the rest existing asphalt concrete will be considered as the effective part. Based on the corresponding material types and conditions, the program will calculate equivalent layer modulus and thickness for the remaining AC layer(s) after milling, as described in Section 5.3.

The rest input and output information for the overlay design is the almost the same as that for the new pavement design (see Section 6.1).

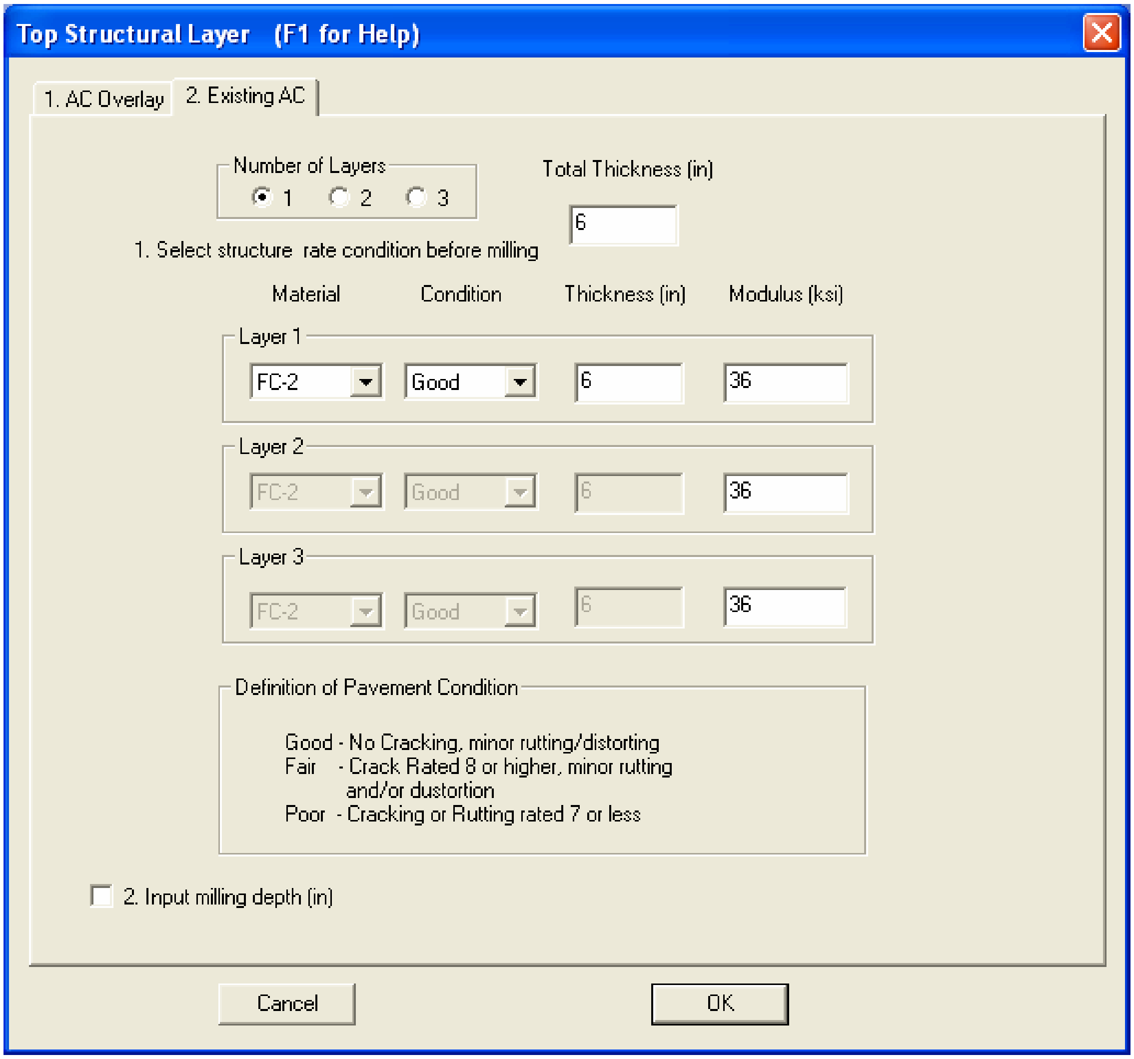


Figure 6.9 Input of the AC layer information: Existing AC layer

7. Key Findings and Recommendations

In this project, the efforts of the research team were focused on the integration of Florida top-down cracking model into mechanistic-empirical (M-E) design framework. A new pavement design tool for top-down cracking has been developed based on energy ratio, which has proven to be a suitable criterion for top-down cracking performance of HMA pavements. The key features of the design tool are summarized below:

- It has been validated on more than thirty field sections.
- The pavement thickness design is optimized for traffic level, reliability, mixture types, and binder selections.
- The thickness optimization is an automated process.
- The tool is capable of pavement life prediction.
- The interactive Windows-based design software has simple inputs and outputs, and user-friendly interface.

In this design software, all the mixture properties used for evaluation of top-down cracking are estimated based on the basic mixture volumetrics, binder viscosity, and the aging model if the measurements of their properties are not available. The research team will continue to evaluate and refine the predictive models for the material properties in the NCHRP 1-42A project, which was recently awarded to the University of Florida.

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APPENDIX A

USER’S MANUAL

FLORIDA TOP-DOWN CRACKING DESIGN TOOL– USER'S MANUAL

Submitted to:

Florida Department of Transportation

Department of Civil & Coastal Engineering
University of Florida
Gainesville, FL 32611

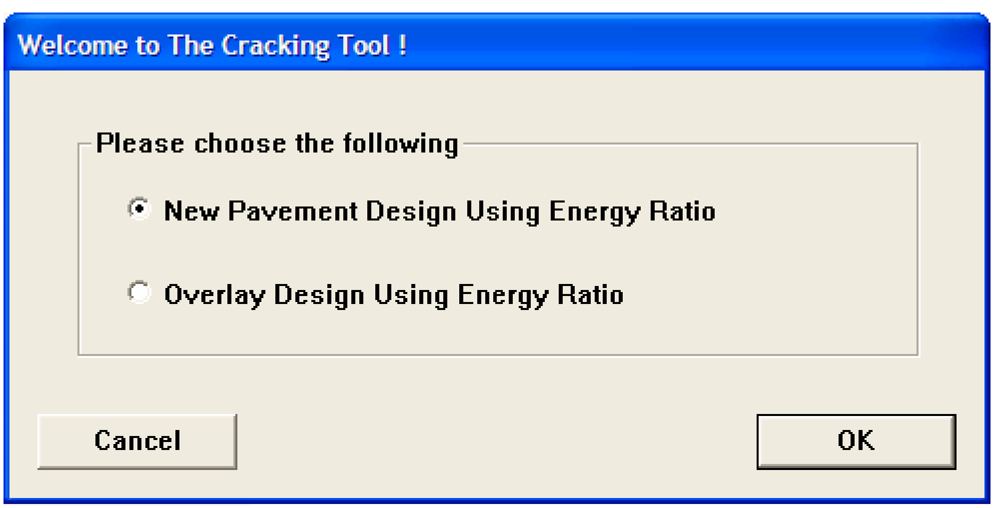
December 2006

TABLE OF CONTENTS

1.0 INTRODUCTION

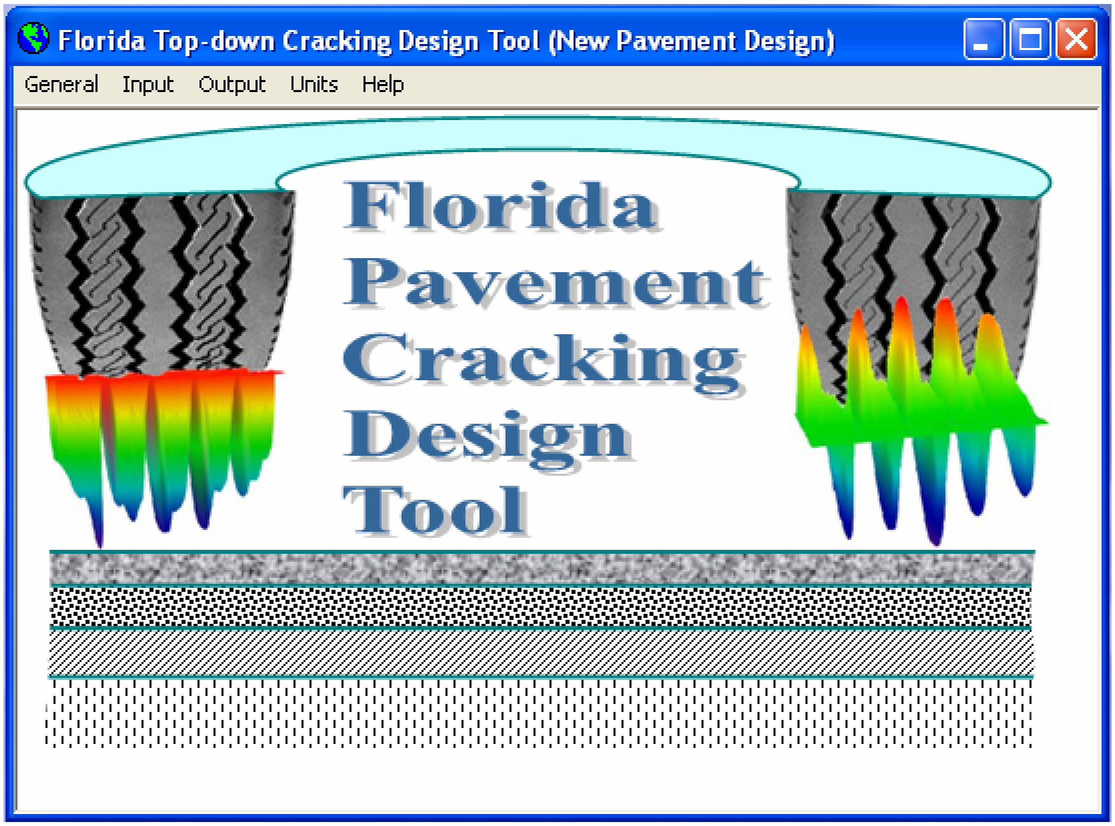
This document provides detailed information on how to use the Florida Top-Down Cracking Design Tool (Software). The information in this document is presented and explained in the order in which the user runs the design software. The cracking design tool includes two modules: new pavement design module and the overlay design module. Both of them are based on the energy ratio criterion for top-cracking design.

When the user starts to run the program, there is a popup window at the very beginning, where the user needs to choose from the following two options: New Pavement Design Using Energy Ratio, or Overlay Design Using Energy Ratio. The user needs to click “OK” to proceed or “Cancel” to exit the program. The “New Pavement Design” and the “Overlay Design” modules are totally independent. Once one of them is chosen, there will not be any interaction between these two modules in the subsequent analysis.



2.0 NEW PAVEMENT DESIGN

If "New Pavement Design Using Energy Ratio" is selected in the previous step, the following main window will be launched.



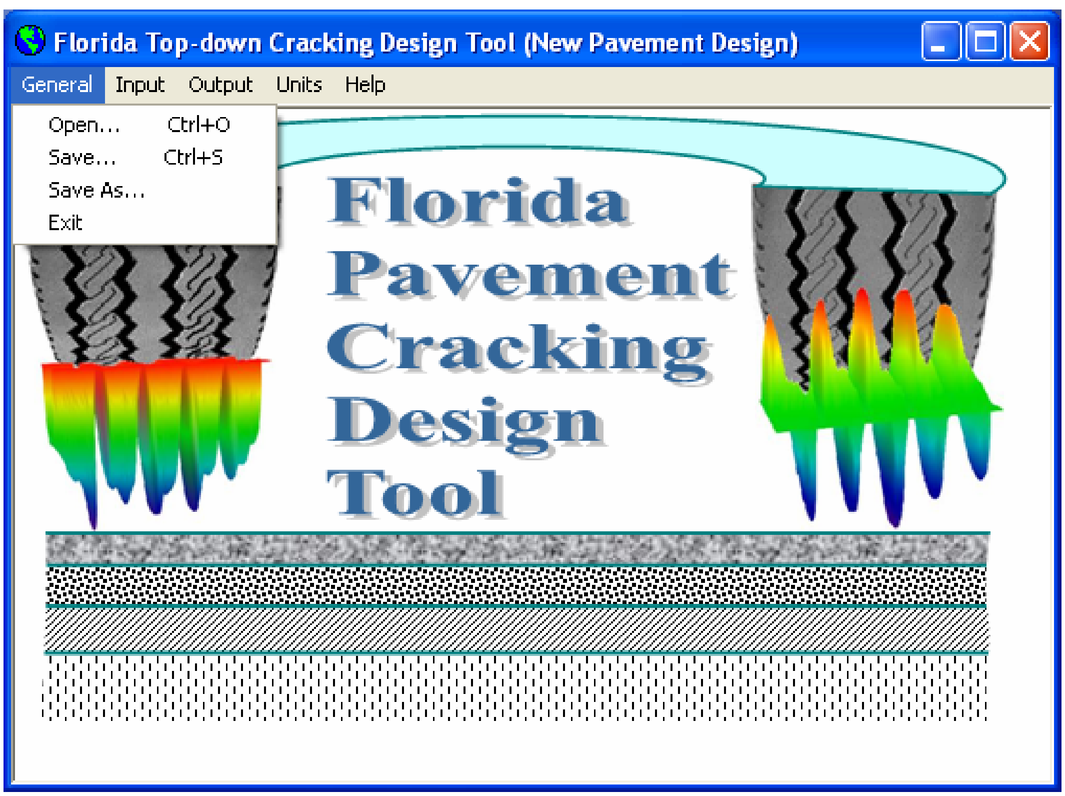
There are five top-down menus included in the main window: General, Input, Output, Units, and Help. The structure of the menus is illustrated in the following figure. As shown in the figure, the key components are located inside the Input and Output menus. The user can press F1 for help at any time when the program is running. The detailed information and instructions associated with each menu choice are further described below.

New Pavement Design Studio

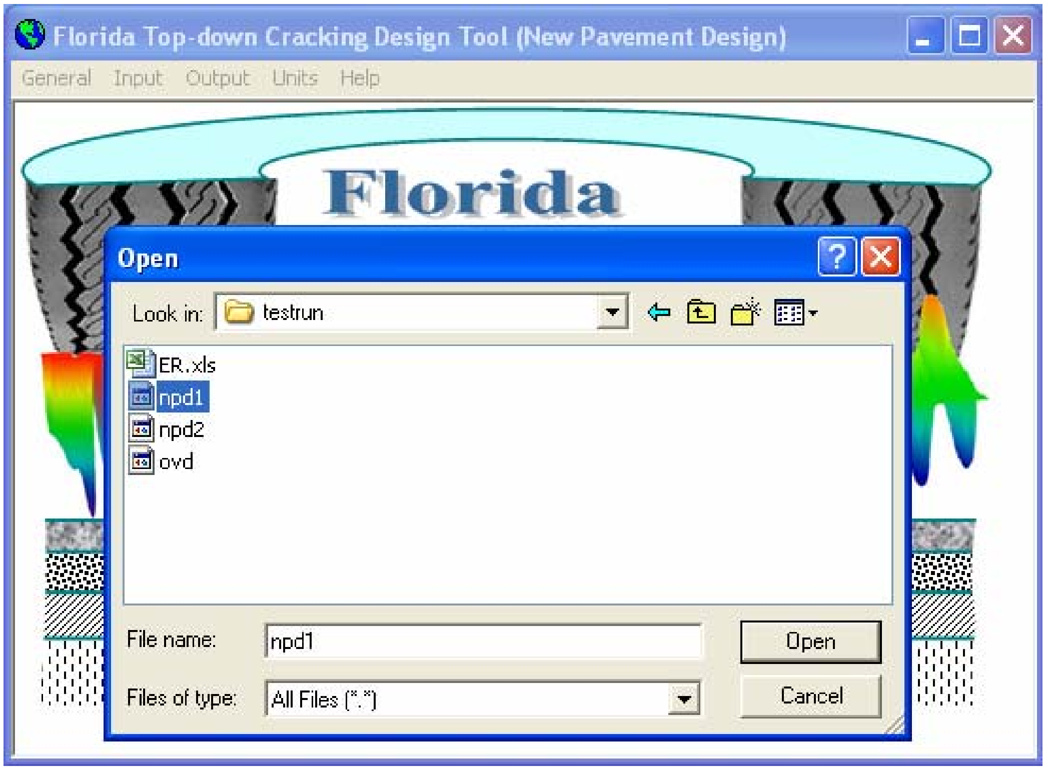
- General
- Input
  - Traffic
  - Reliability
  - Climatic Information
  - Top Structure (AC) Layer
  - Base Group
- Output
  - ER value
  - Optimum thickness
  - Optimization curve
  - ER-pavement life curve
- Units
- Help

2.1 GENERAL

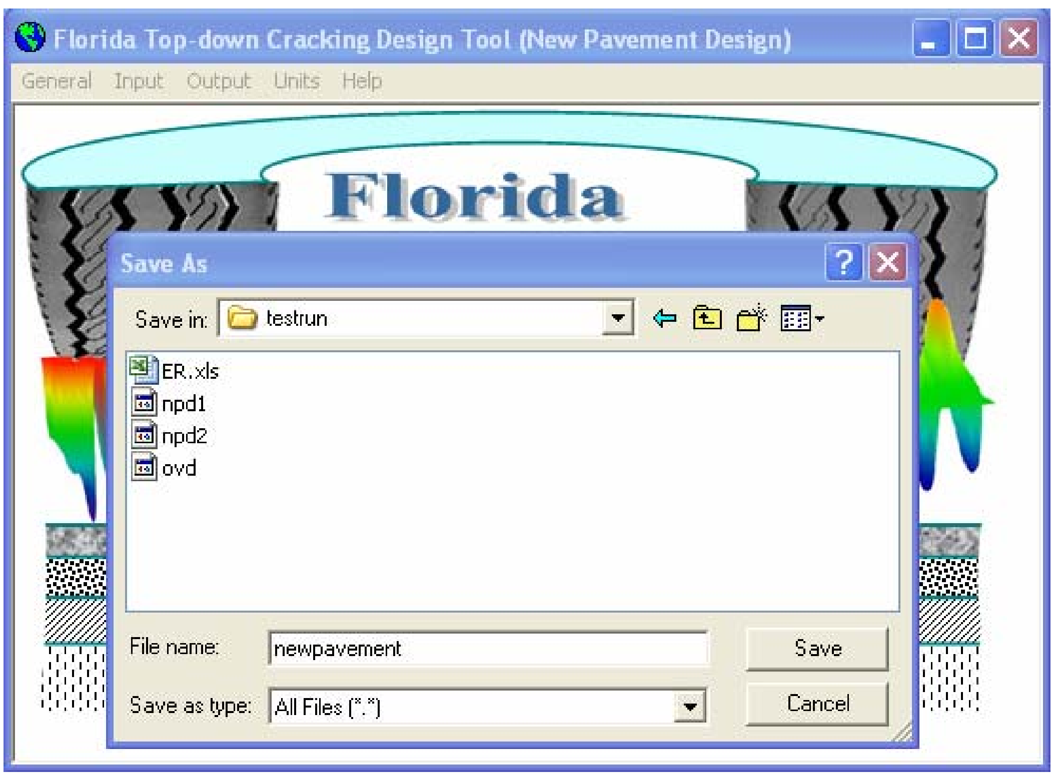
As shown in the following figure, there are four choices inside "General": Open, Save, Save As, and Exit.



Open: open an existing (saved) project



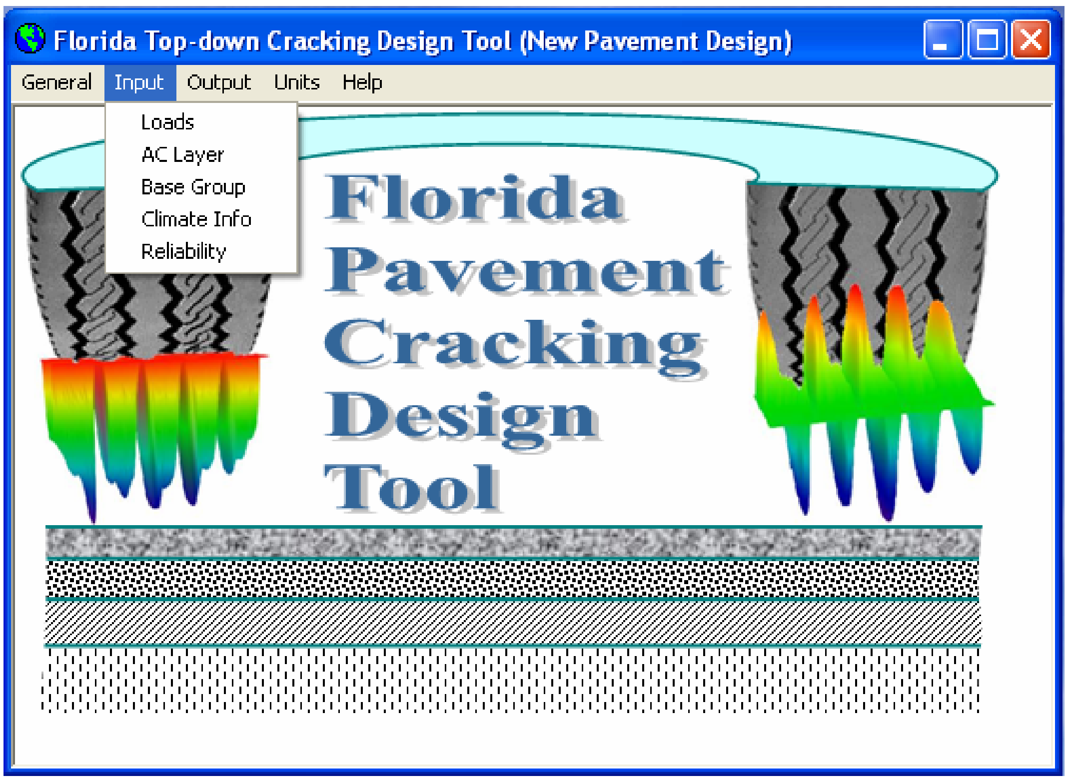
Save and **Save As**: save the current project. All the input information will be saved.



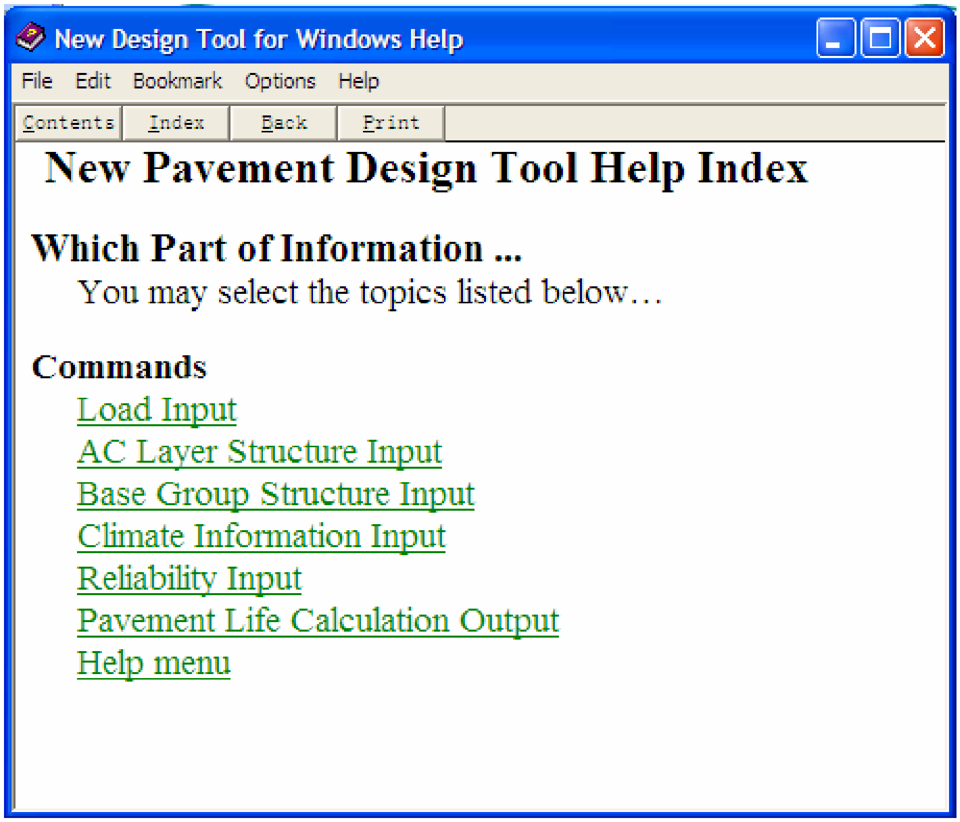
Exit: exit the current program.

2.2 Input Menu

The input menu includes the following basic components: traffic, reliability, climatic information, AC layer information, and the structural information for the base and stabilized subgrade. As shown in following figure, “Loads” corresponds to the traffic information input; “AC Layer” corresponds to mixture selection and AC structural information; “Base Group” corresponds to the structural information for the base and stabilized subgrade; “Climate Info” and “Reliability” corresponds to the climatic and reliability information, respectively. The



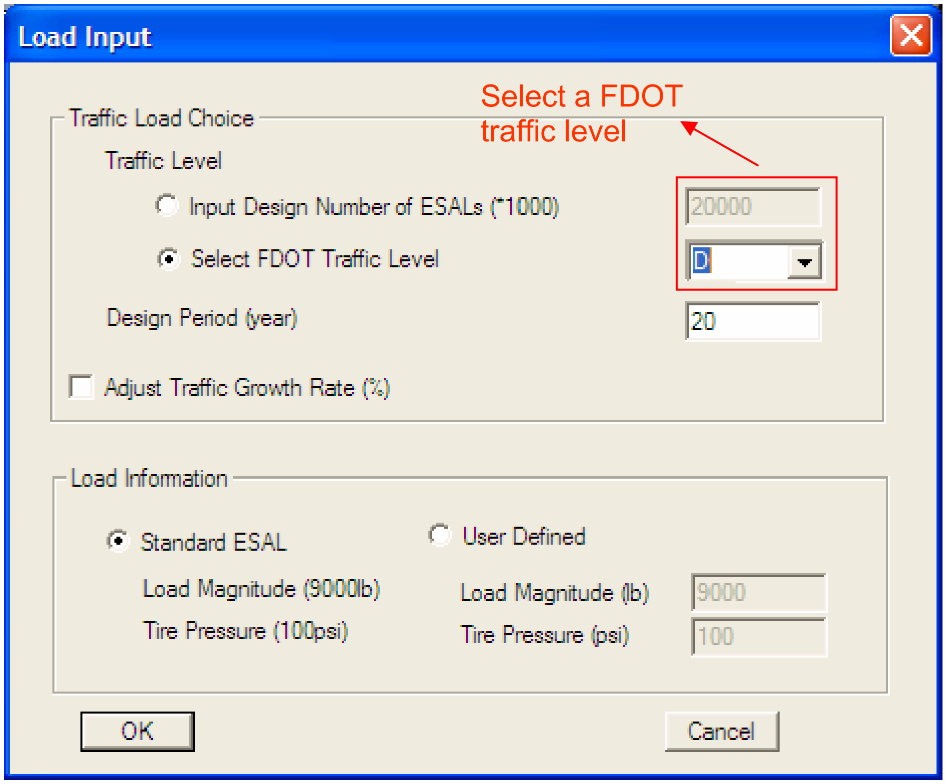
input order is arbitrary. The user can start from any of the input menu options. There is no requirement that the user need to go through all the input menus because default values are provided for all the information required. At any time, the user can press F1 for help. For example, if there use has not started to open any input window, pressing F1 will pop up the following Help Index window:

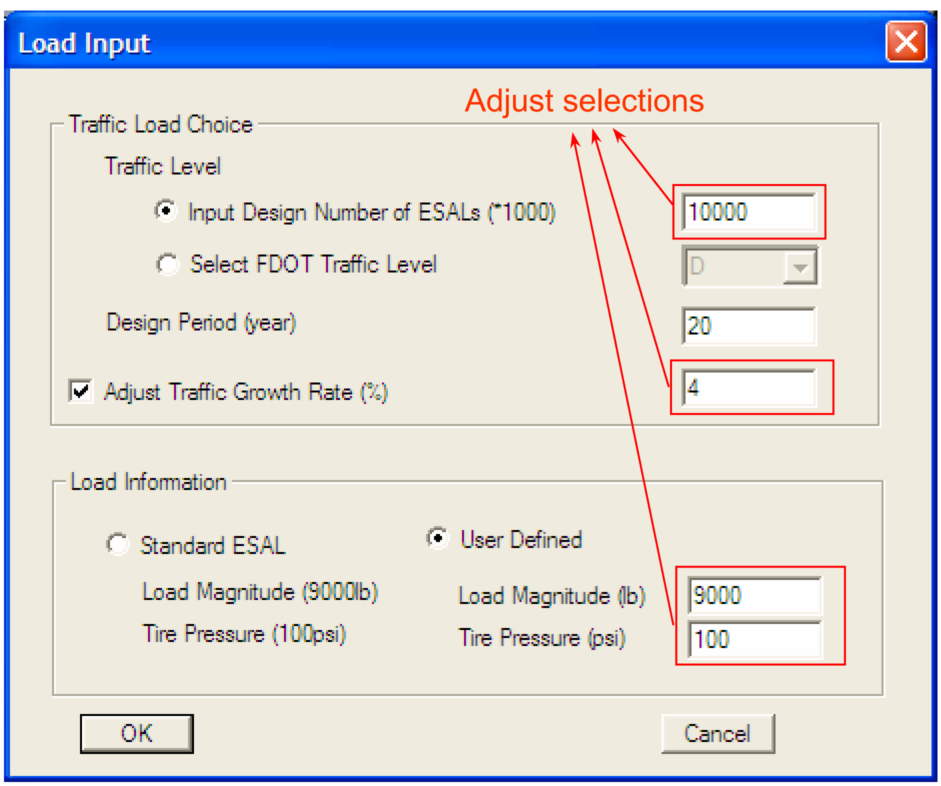


The explanation for each item of the input menu is given in the following sections, but it is not in the order as it appears in the input menu.

2.2.1 Traffic Input

In the Level 3 analysis, the traffic input is simple, as illustrated in the following figures. The user only needs to specify the traffic level by inputting the total design number of ESALs (Equivalent Single Axle Loads) or selecting a FDOT traffic level; specify the pavement design life and/or adjust the traffic growth rate. By default, the traffic growth rate is 2% per year. For the load information, the user can choose the "Standard ESAL", which is equivalent to 9000 lb load with tire pressure equal to 100 psi.

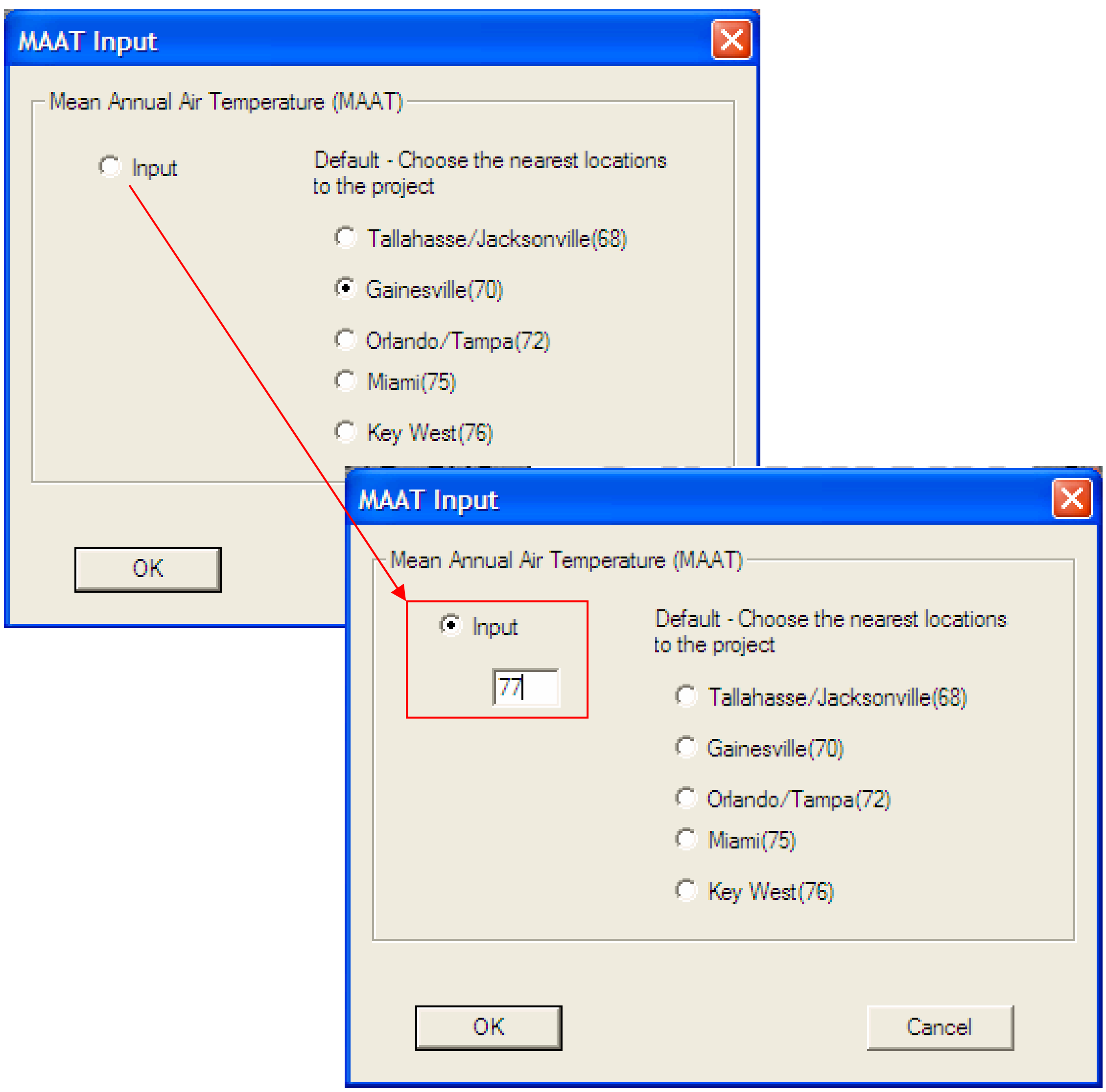

Load Input
Traffic Load Choice
Traffic Level
Input Design Number of ESALs (*1000)
Select FDOT Traffic Level
Design Period (year)
Adjust Traffic Growth Rate (%)
20000
D
20
Load Information
Standard ESAL
Load Magnitude (9000lb)
Tire Pressure (100psi)
User Defined
Load Magnitude (lb)
Tire Pressure (psi)
9000
100
OK
Cancel
Select a FDOT traffic level


Load Input
Traffic Load Choice
Traffic Level
Input Design Number of ESALs (*1000)
Select FDOT Traffic Level
Design Period (year)
Adjust Traffic Growth Rate (%)
10000
D
20
4
Load Information
Standard ESAL
Load Magnitude (9000lb)
Tire Pressure (100psi)
User Defined
Load Magnitude (lb)
Tire Pressure (psi)
9000
100
OK
Cancel
Adjust selections

As shown in the second figure, the user can also make adjustments to the travel level, the traffic growth rate, as well as the load information by inputting user-defined values.

2.2.2 Climatic Information

In the climatic information input, the designer only needs to select the nearest locations to the project. The current model only takes the MAAT of the selected location as input. The user can also input the MAAT of the project location if it is available.

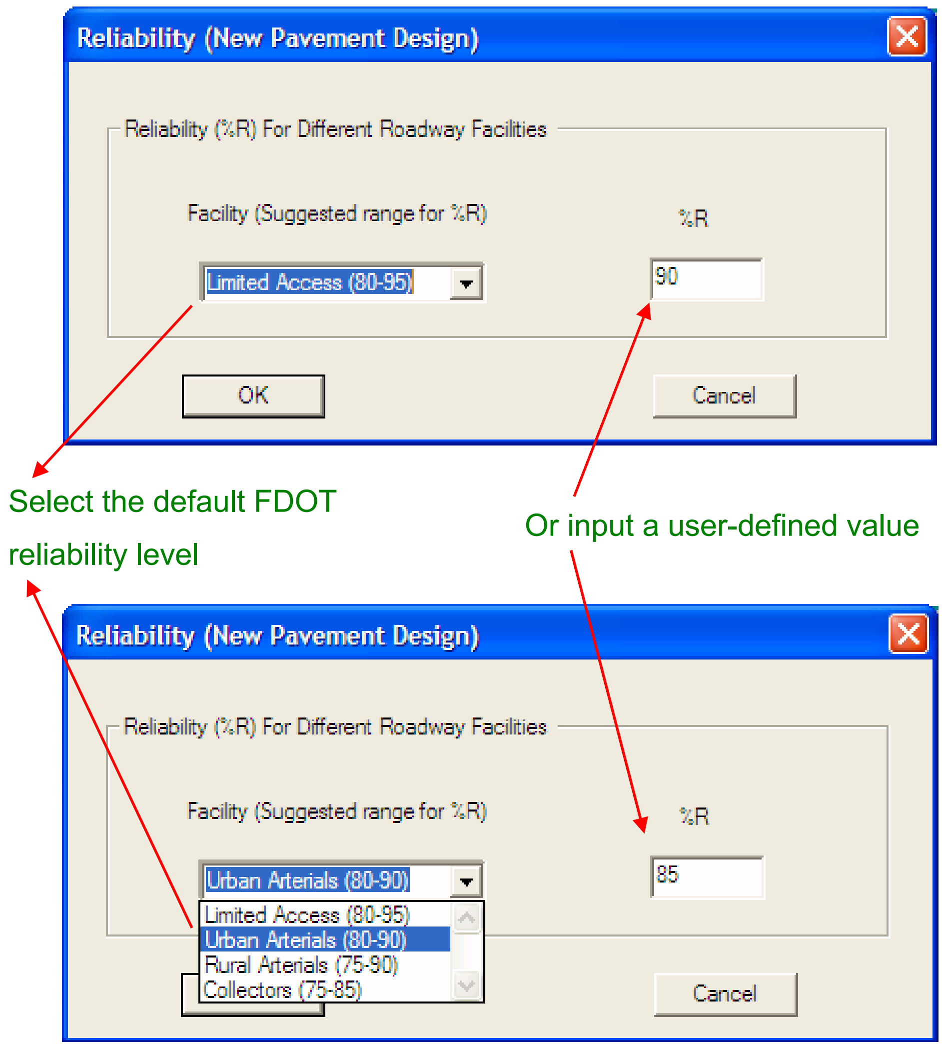


2.2.3 Reliability Input

The FDOT specifies different reliabilities for different roadway facilities for new pavements and rehabilitated pavements (for example, for new pavements, 80-95% for limited access, 80-90% for urban arterials, 75-90% for rural arterials, etc.), as shown in the following table provided in the *Florida Flexible Pavement Design Manual*.

Facility	New	Rehabilitation
Limited Access	80 - 95	95 - 99
Urban Arterials	80 - 90	90 - 97
Rural Arterials	75 - 90	90 - 95
Collectors	75 - 85	90 - 95

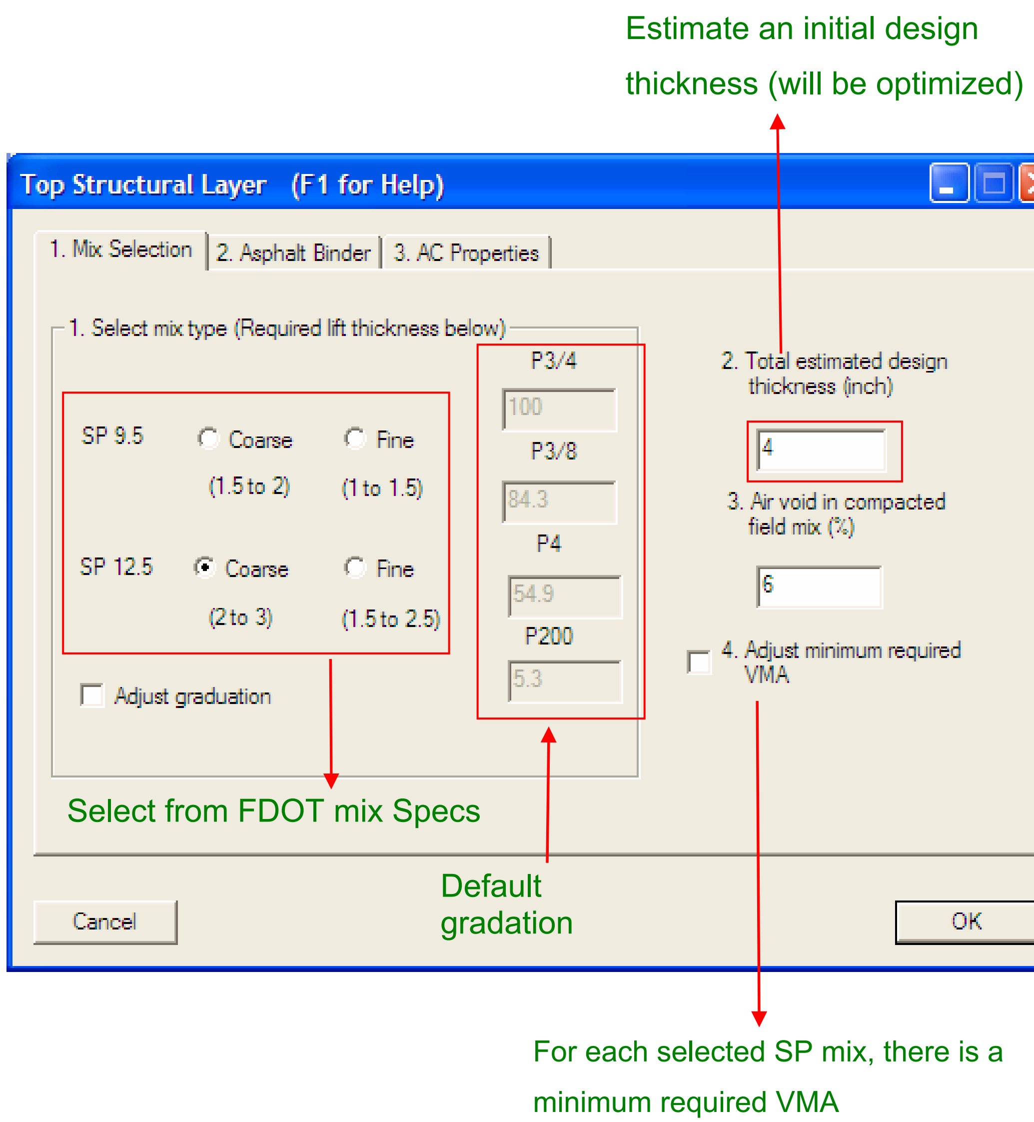
The designer has the flexibility in selecting the values that best fits the project when choosing the reliability. As shown in the following, the user need to make the selection of the types of facility, each of which corresponds a range of reliability (%R) suggested by FDOT. A default value is selected within the suggested range. The user can also adjust the default value, which, however, should be within the suggested range. As mentioned in the report, the reliability level together with traffic level will be used to determine the minimum required (optimum) Energy Ratio for the pavement.



2.2.4 Top Structure (AC) Layer

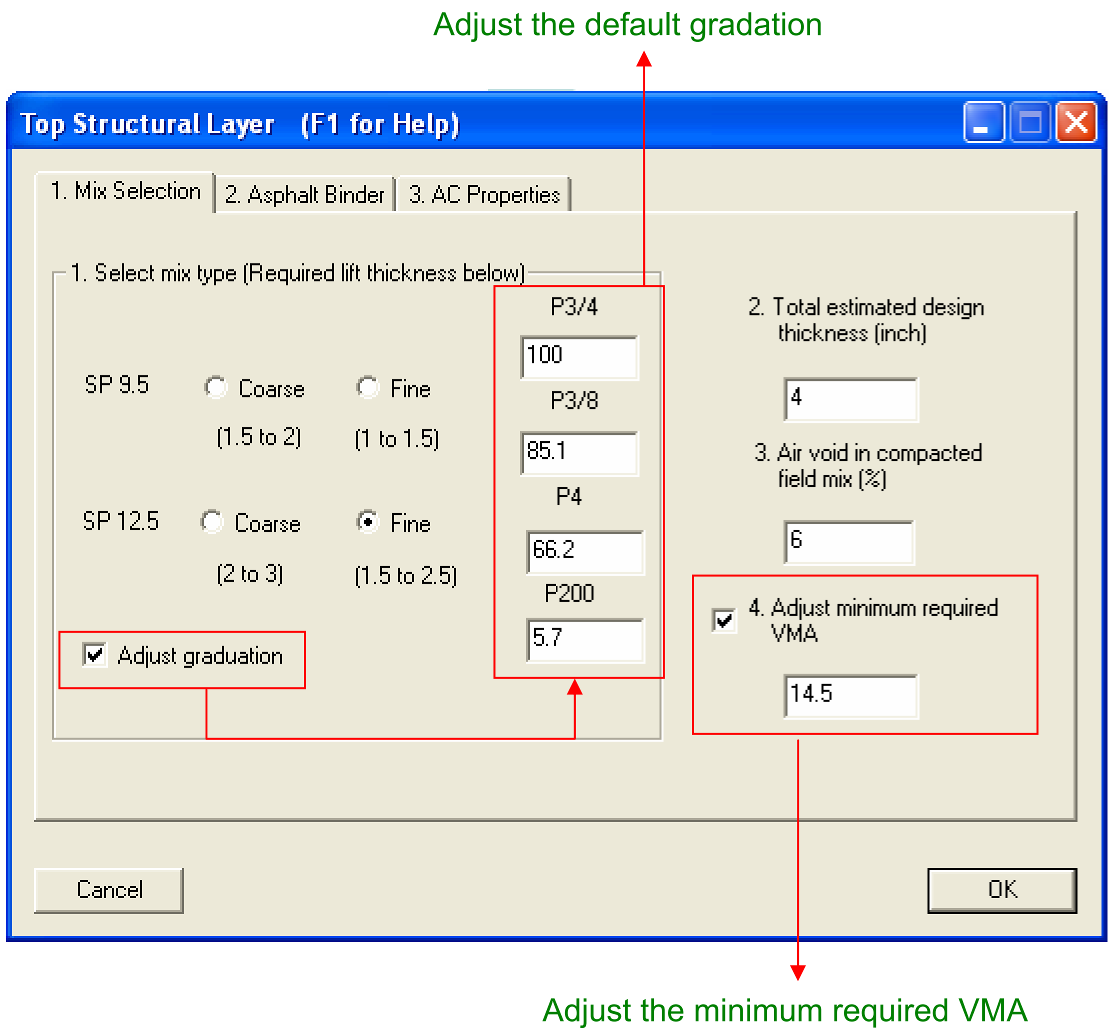
The AC layer design includes mix selection and structural information, binder selection, and determination of the basic fracture properties of the mixture. The input window for the AC layer includes three tabs, labeled in a sequential order as: 1. Mix Selection, 2. Asphalt Binder, and 3. AC Properties.

Insider Tab 1 (Mix Selection), the user first needs to select the mix from 4 basic types (SP9.5 and SP12.5 coarse/fine mixtures) specified by FDOT. For each mix, there is a

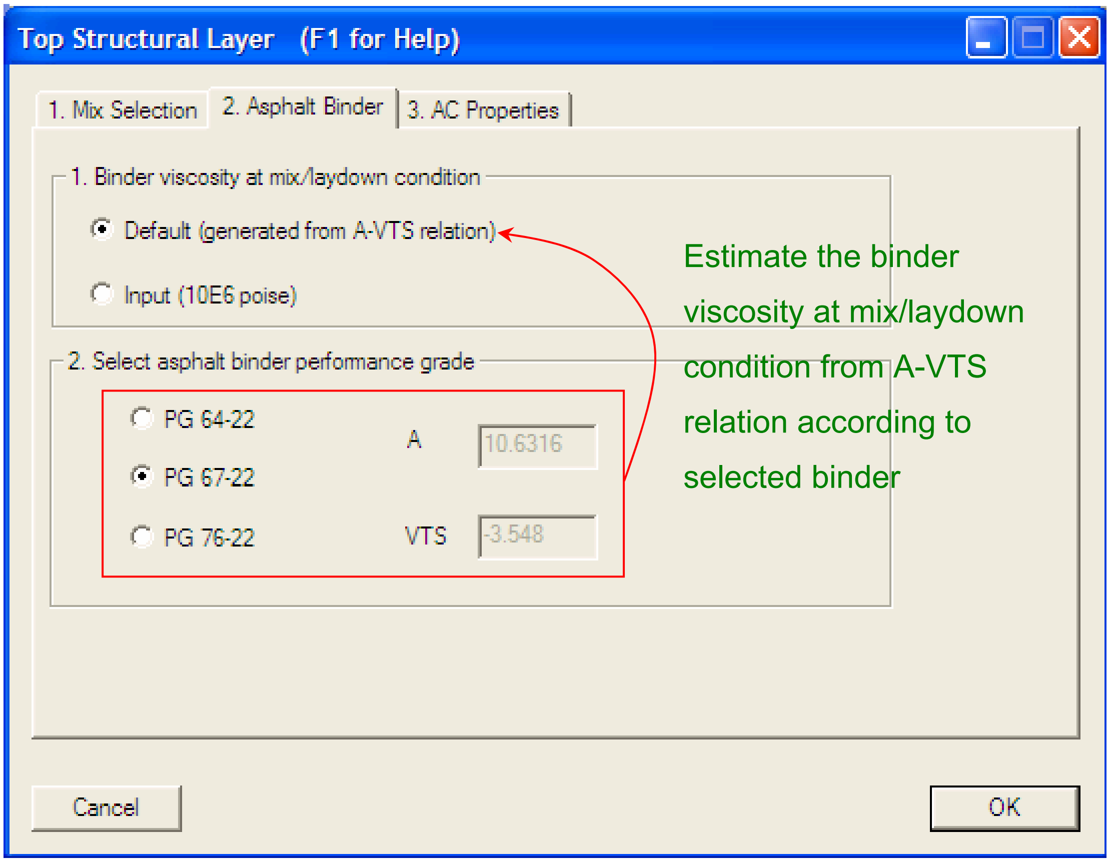


default gradation, which was suggested by the research team based on their work and experience on graduation. The designer also needs to input an estimated design thickness (default value is 4") and air voids in compacted field mix (default value is 6%). The estimated design thickness will be updated automatically in the optimization process. For each mix type provided, there is a suggested minimum required VMA value. In the design process, this minimum required VMA value will be used to calculate the effective asphalt content by volume (V_{beff}), which is needed to estimate the dynamic modulus |E*| of the mixture from the master curve.

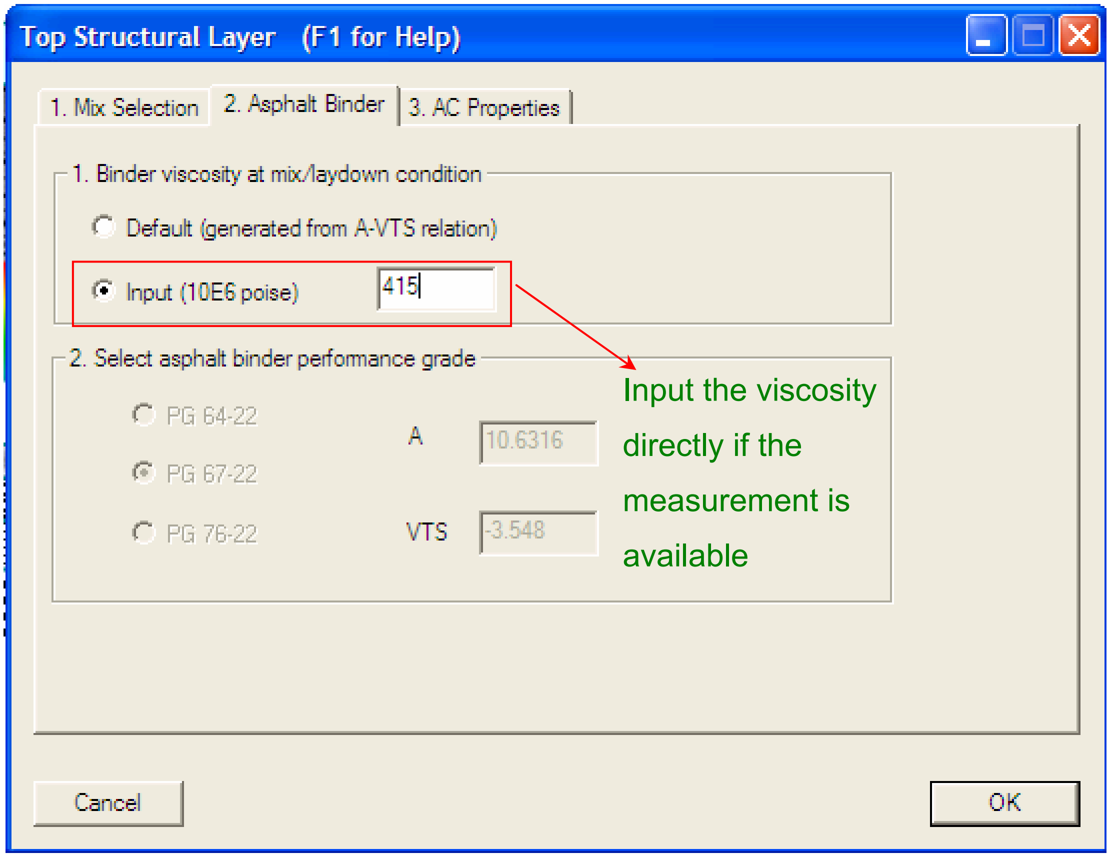
As illustrated in the following figure, the user can also make adjustment to the default graduations by changing the percent passing of several key sieve sizes, as well the minimum required VMA value.



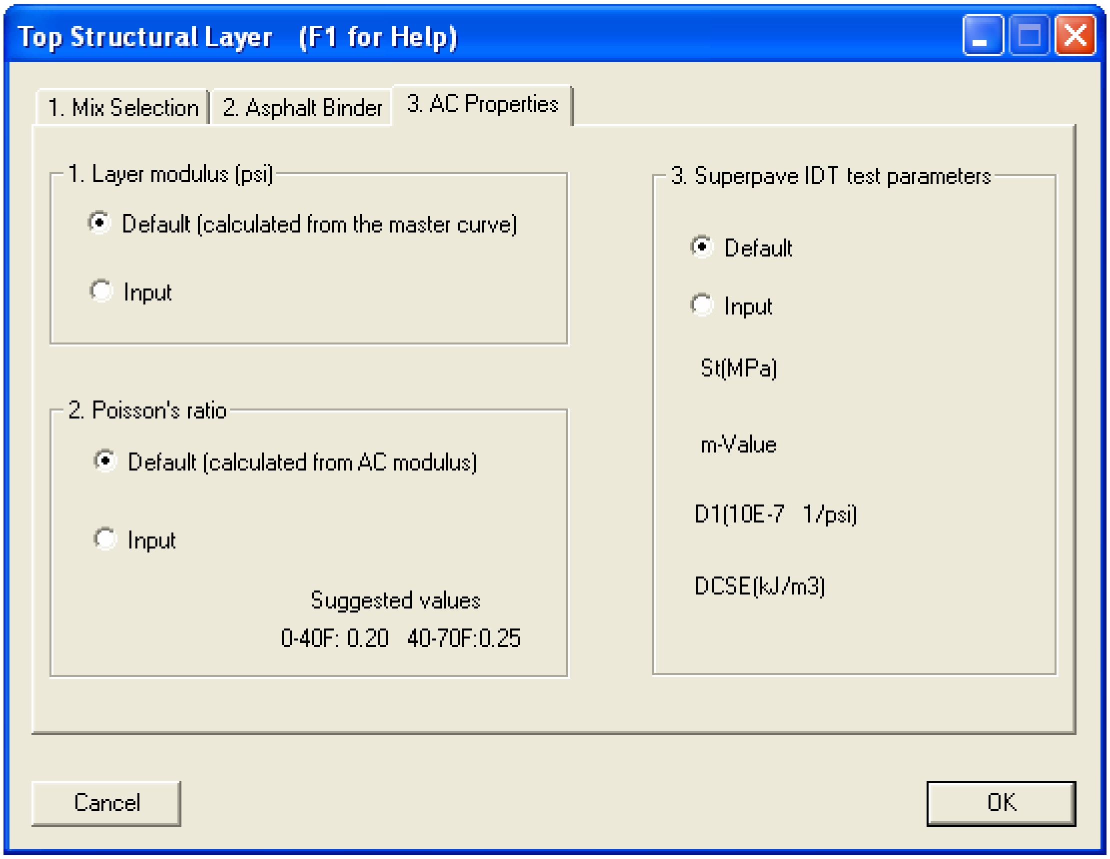
Tab 2 inside the AC layer input window is concern with binder viscosity information and the asphalt binder selection. If the user choose the generate the binder viscosity from the A-VTS relation (by default), he/she needs select one from the three commonly used asphalt binders (PG 64-22, PG67-22, or PG76-22). Based on this selection, the program automatically calculates the binder viscosity at mix/laydown condition by using the A-VTS relation. The temperature at which the viscosity is calculated is set at 50^{o}F (10°C), which is believed to be representative of the intermediate in-service temperatures associated with conditions that are conducive to top-down cracking.



In lieu of using the A-VTS relation, the user can input the binder viscosity directly if the measurement is available. It is worth mentioning that the viscosity inputted here should be the value at 10°C, at which a direct measurement is usually not available. An alternatively way is to measure the binder viscosity at two other temperatures (for example, 25°C and 60°C) and generate an A-VTS relation based on the measurements at these two temperatures. The user can then calculate the viscosity at 10°C using the generated A-VTS relation and input the result into the viscosity field shown in the following figure.

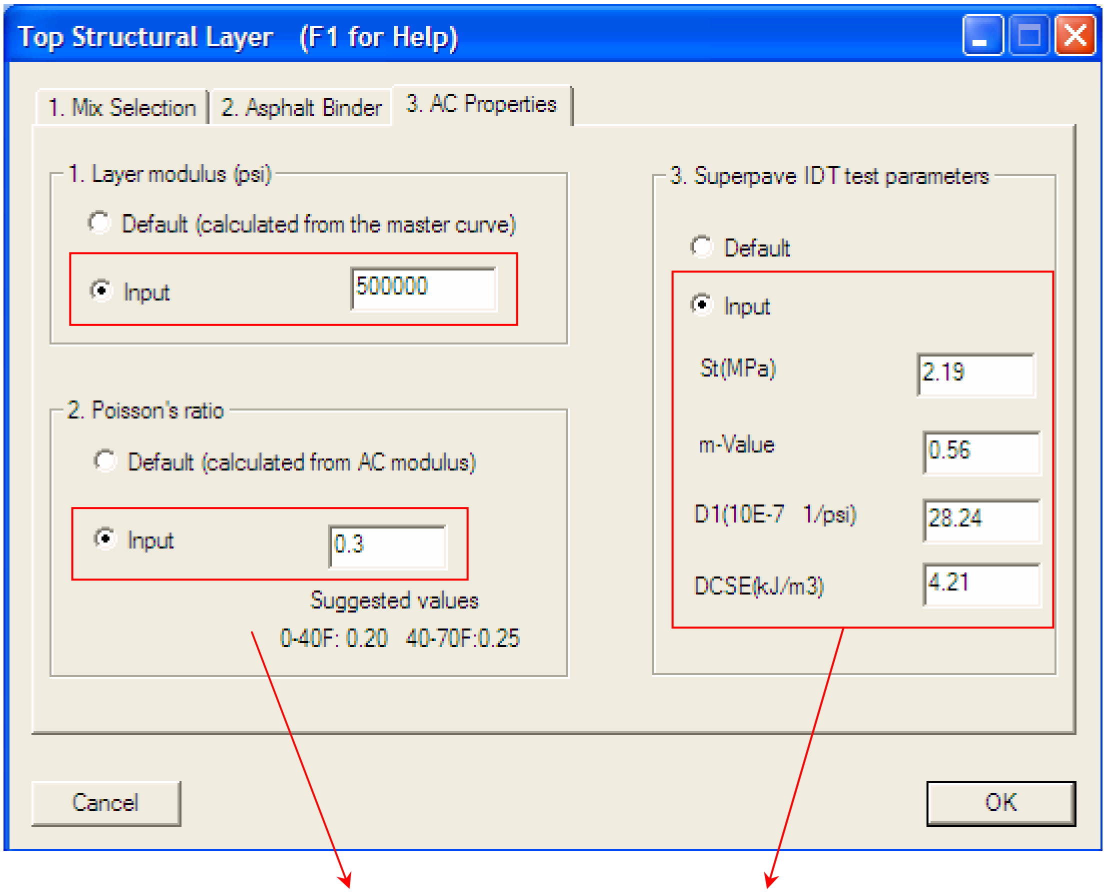


The final step in the AC layer information input is to determine the mixture properties, including the elastic properties (such as $|E^*|$ and ν) as well we the fracture properties (such as creep parameters D_1 and m, tensile strength S_t, and the dissipated creep strain energy limit $DCSE_f$). As shown in the following figure (Tab 3 of AC layer window), the user may choose to determine these properties in a default way – let the program generate these values based on the material models described in the report.



These material properties generated from the material models will be set as the default values at the time right after construction (i.e., t = 0). For pavement life calculation, the values of the material properties will be automatically updated (in the background) at each month throughout the pavement life based on the aging model.

The user can also input the material properties directly by checking the "Input" buttons located inside Tab 3, if the corresponding lab measurements are available, as illustrated in the next figure. In this case, the software is actually used to evaluate the cracking performance of an existing pavement, because the material properties are specified (at a fixed time point) and are not allowed to vary. Correspondingly, in the output window, only ER value and ER-thickness curve will be given but without the ER-pavement life curve.

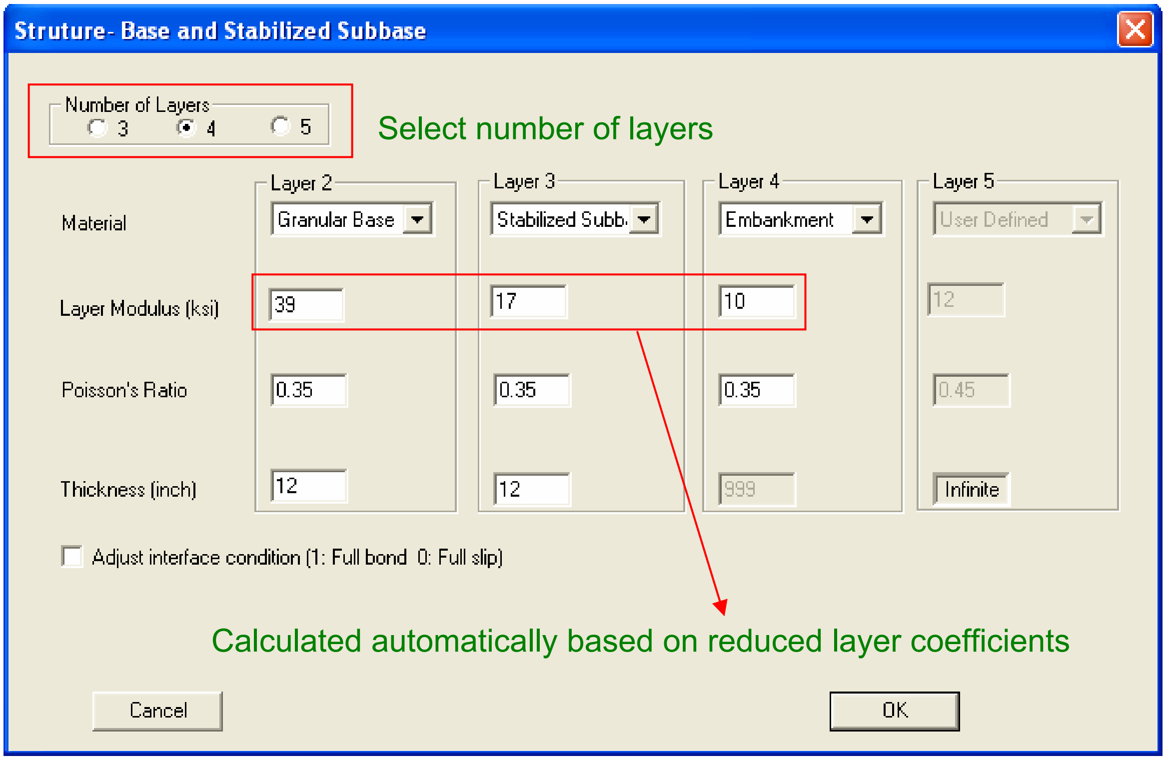


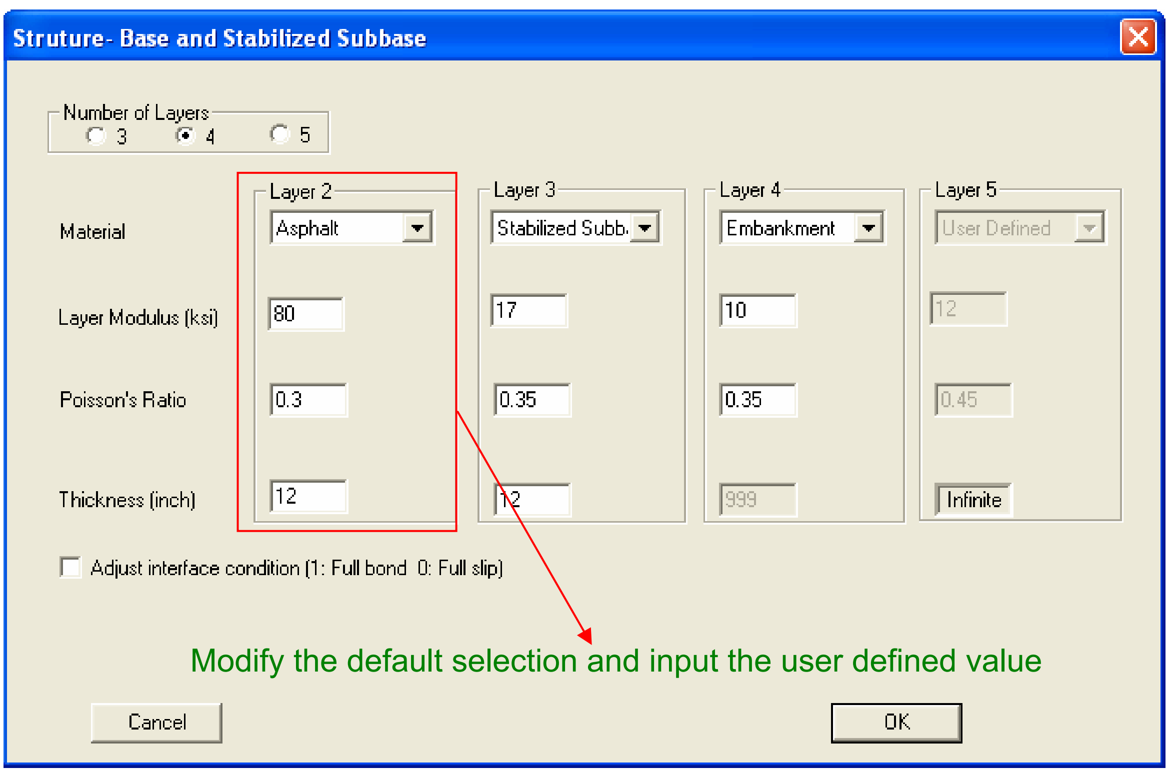
Input the all the AC properties needed if their lab measurements are available

2.2.5 Base Group

The remaining item of the input menu is regarding the structural information for the base and stabilized subgrade. This information will be used to evaluate structural effects on the cracking performance of the AC layer. For example, the stresses in the AC layer strongly depend on the thickness and stiffness of the base layers.

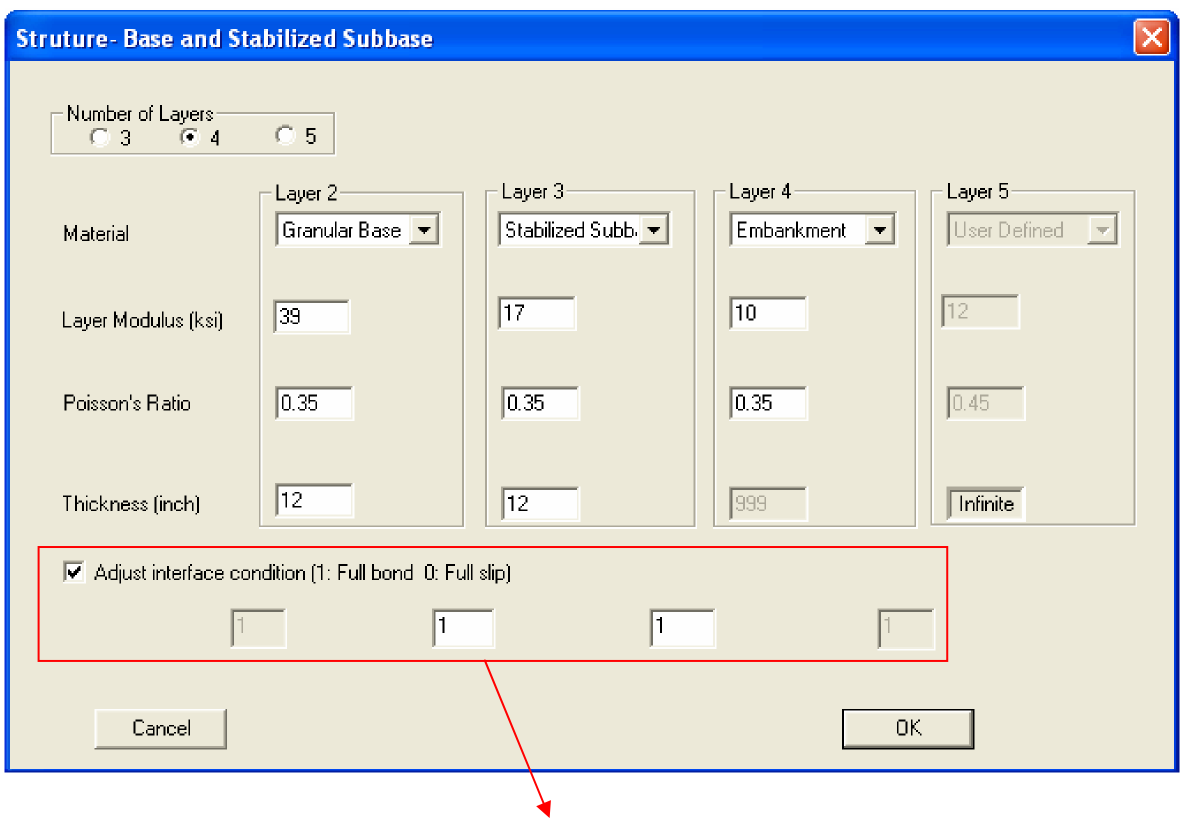
As shown in the following figures, the user first needs to select the total number of layers (including the AC layer). For each layer below the AC layer, the user can select the material from the drag-down field. The FDOT has recommendations for the base group materials


Struture- Base and Stabilized Subbase
Number of Layers
3
4
5
Select number of layers
Layer 2
Layer 3
Layer 4
Layer 5
Material
Granular Base
Stabilized Subb.
Embankment
User Defined
Layer Modulus (ksi)
39
17
10
12
Poisson's Ratio
0.35
0.35
0.35
0.45
Thickness (inch)
12
12
999
Infinite
Adjust interface condition (1: Full bond 0: Full slip)
Calculated automatically based on reduced layer coefficients
Cancel
OK


Struture- Base and Stabilized Subbase
Number of Layers
3
4
5
Layer 2
Layer 3
Layer 4
Layer 5
Material
Asphalt
Stabilized Subb.
Embankment
User Defined
Layer Modulus (ksi)
80
17
10
12
Poisson's Ratio
0.3
0.35
0.35
0.45
Thickness (inch)
12
12
999
Infinite
Adjust interface condition (1: Full bond 0: Full slip)
Modify the default selection and input the user defined value
Cancel
OK

(such as, granular base, graded aggregate, asphalt base, etc.). The properties for the selected materials are determined automatically by the program based on the reduced layer coefficients. The user can also modify the default values corresponding to each selection or input the user-defined material type and properties.

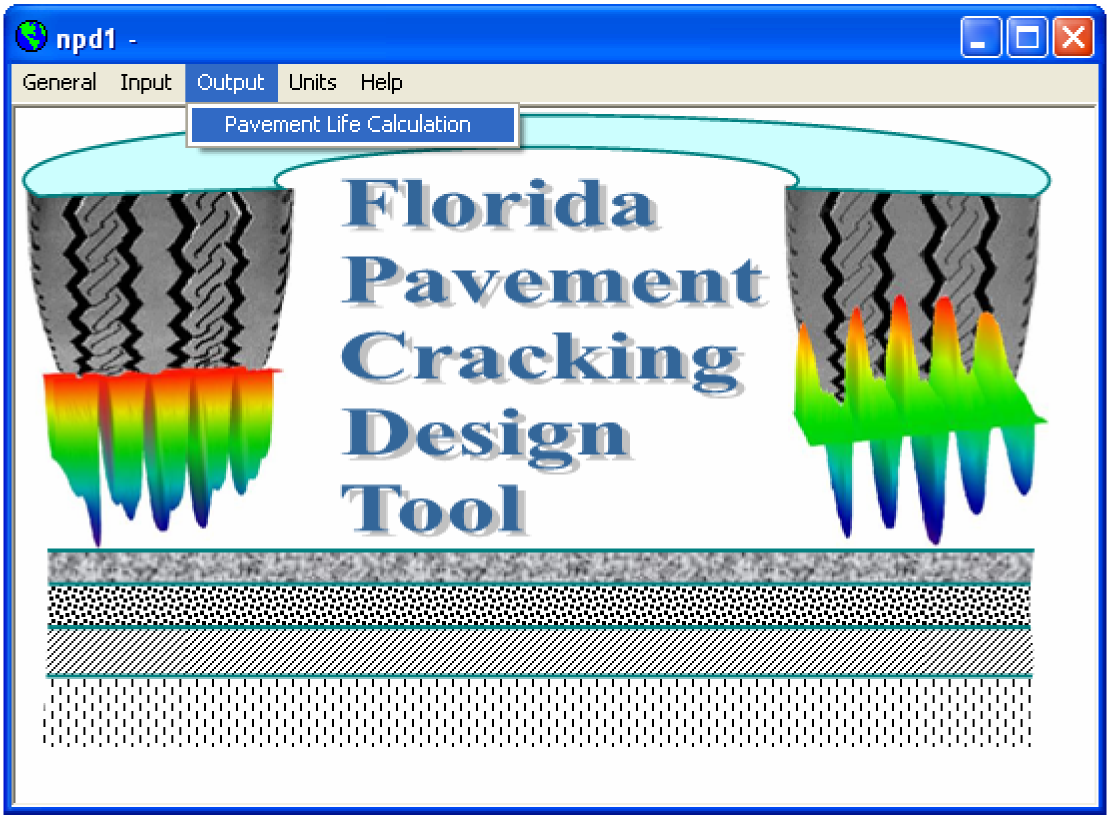
The interfaces between two adjacent layers are assumed to be perfectly bonded. By default, the interface condition number is 1. The user can also adjust this number by checking the in front of "Adgust interface condition," as shown in the following figure. The condition number should be between 0 and 1, which correspond to full slip and full bond, respectively.



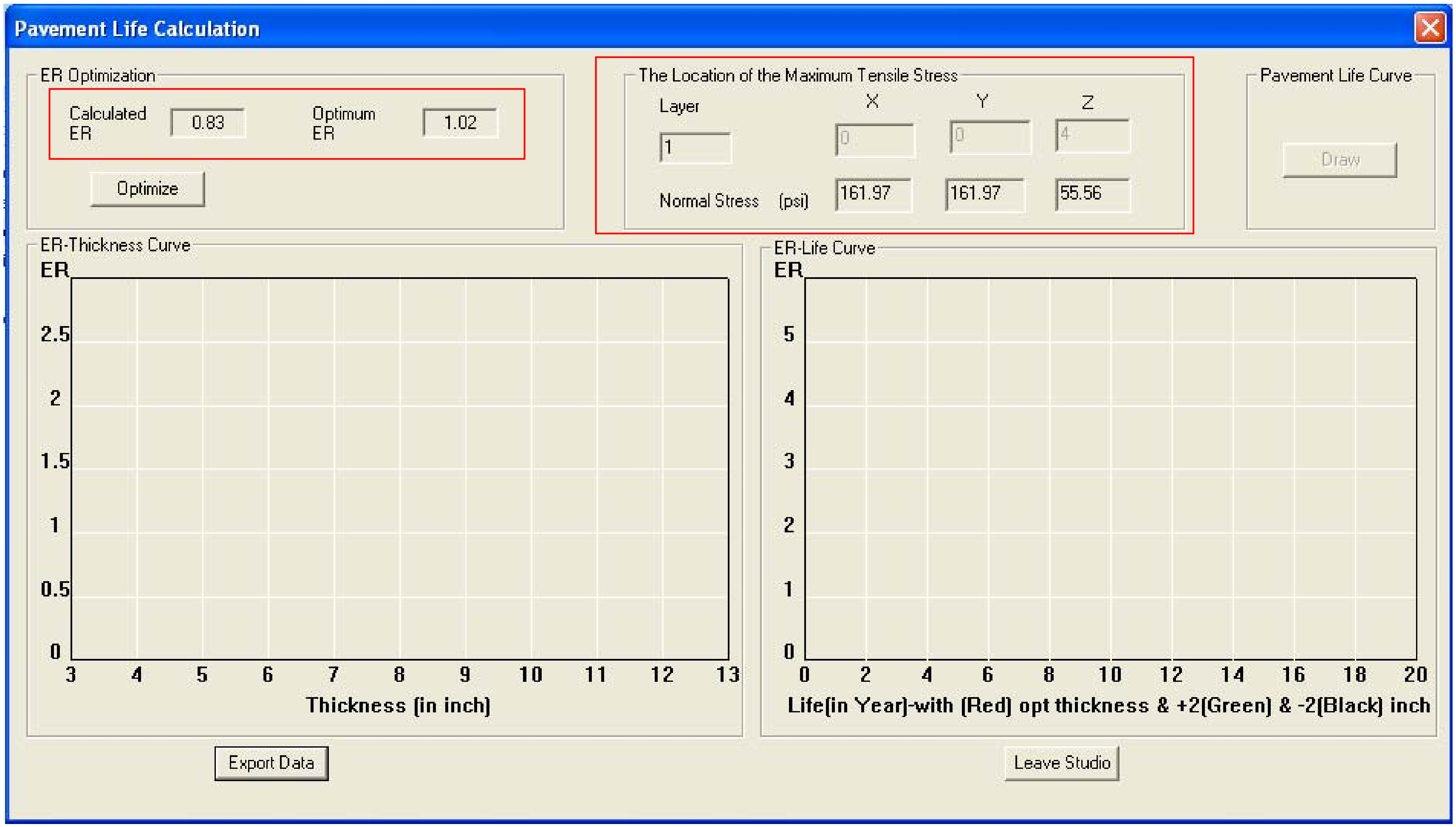
Adjust the interface condition between full slip and full bond

2.3 Output Window

Once the user finishes the input, go to the output menu as shown in the following figure. There is only one option in output menu: pavement life calculation.

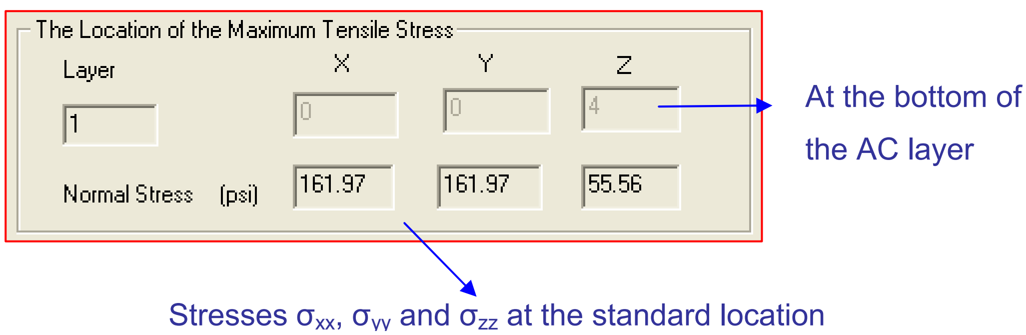


After clicking "Pavement Life Calculation", one output window will be popped up. The window layout is shown in the following figure. The program already calculated the maximum tensile stress inside the pavement (bottom of AC layer) and the Energy Ratio based on tensile stress based on the input information. The results for the ER value, the location and magnitude of the tensile stress are outputted into the "Pavement Life Calculation" window, as marked with in the following figure. No curves will be drawn in the two graph frames until further action is taken.


Pavement Life Calculation
ER Optimization
Calculated ER
0.83
Optimum ER
1.02
Optimize
The Location of the Maximum Tensile Stress
Layer
1
X
Y
Z
0
0
4
Normal Stress (psi)
161.97
161.97
55.56
Pavement Life Curve
Draw
ER-Thickness Curve
ER
2.5
2
1.5
1
0.5
0
3 4 5 6 7 8 9 10 11 12 13
Thickness (in inch)
ER-Life Curve
ER
5
4
3
2
1
0
0 2 4 6 8 10 12 14 16 18 20
Life(in Year)-with (Red) opt thickness & +2(Green) & -2(Black) inch
Export Data
Leave Studio

2.3.1 ER and Stress Output

The information given in the marked area of the upper-middle part of the output window is for the maximum tensile stress is given. For example, the following figure shows that the maximum tensile stress occurs at the bottom of the AC layer: x = 0, y = 0, z = 4 corresponds to the location right beneath the tire load. The initial AC thickness was given as 4 in, so z = 4 is at the bottom of the AC layer. The magnitude of the maximum stress (σ_{xx}= σ_{yy}) at this location shown in the following figure is 161.97 psi and the compressive stress (σ_{zz}) is 55.56 psi.

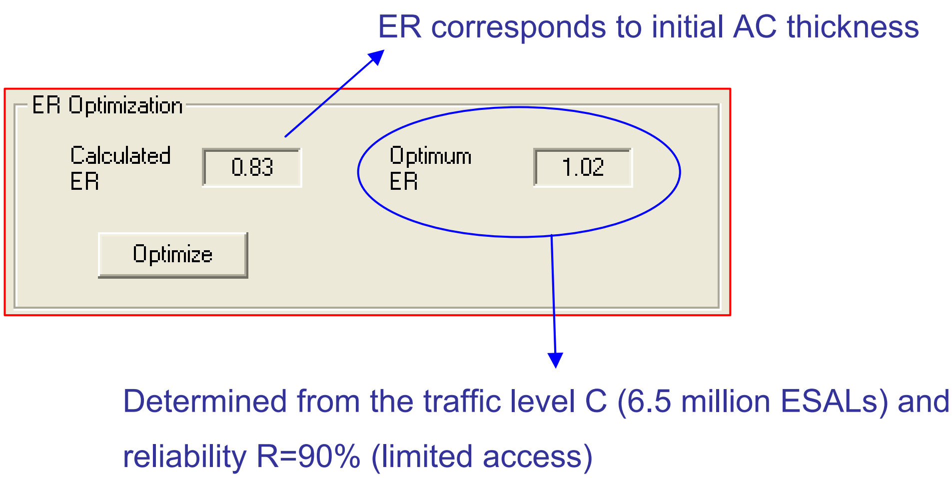


The ER value given in the upper-left corner of the output window was calculated from the following formula

$$ER = f\,(S_t, \sigma_{max}) * DCSE_f \,/\, (m^{2.98} * D_1) \quad \text{and}$$

$$f\,(S_t, \sigma_{max}) = 0.0299 * \sigma_{max}^{-3.10} * (6.36\text{-}S_t) + 2.46 * 10^{-8}$$

As shown in the following figure, the calculated ER is 0.83, which corresponds to the initial AC thickness (4 in). If the material properties of AC layer were inputted directly from measurements (see Section 2.1.4), then the calculated ER corresponds to the time when the material properties were evaluated; if the AC properties were by default (estimated in the design process), the calculated ER corresponds to the end of the pavement life.

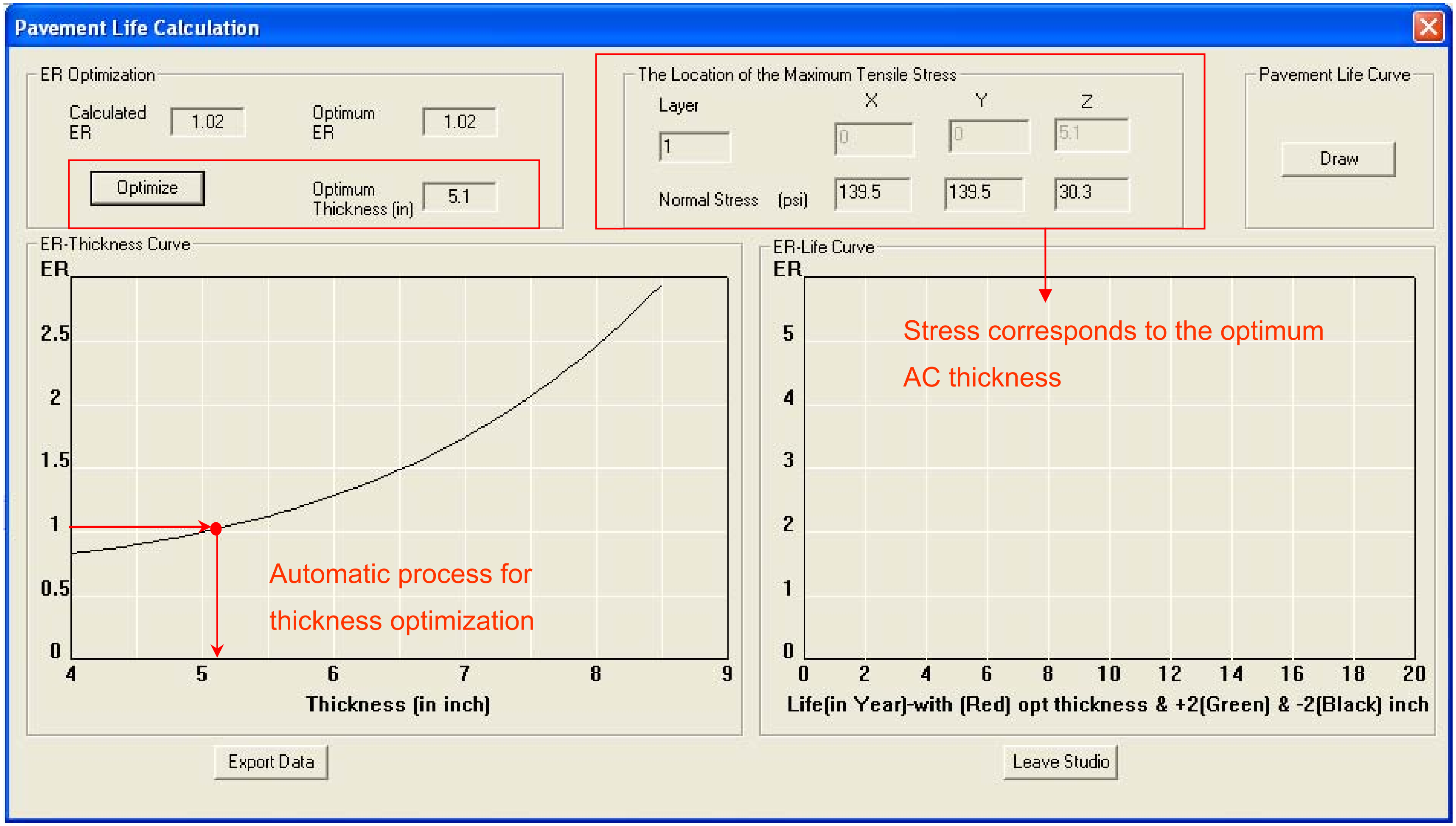


The Optimum ER value next to the calculated ER (in the above figure) was calculated from Eq. (4.3) in the report. It depends on both the traffic level and reliability level. The traffic and reliability factors in Eq. (4.3) were determined from Figure 4.8 and 4.9, respectively. For example, for FDOT traffic level C and a reliability level R=90%, the optimum ER value is 1.02, as shown in the highlighted field in the above figure.

The user needs to compare the calculated ER value with the minimum required ER shown in the "Optimum ER" field. If the calculated ER is not approximately equal the optimum ER, the user can optimize the AC thickness by clicking the "optimize" button. It is worth mentioning that the user can always click the "optimize" button to get the ER-thickness curve even the optimization is not necessary (i.e., calculated ER is equal to the optimum ER). From ER-thickness curve, the user can see how ER values changes with the AC thickness, which will be good for sensitivity analysis.

2.3.2 AC Thickness Optimization

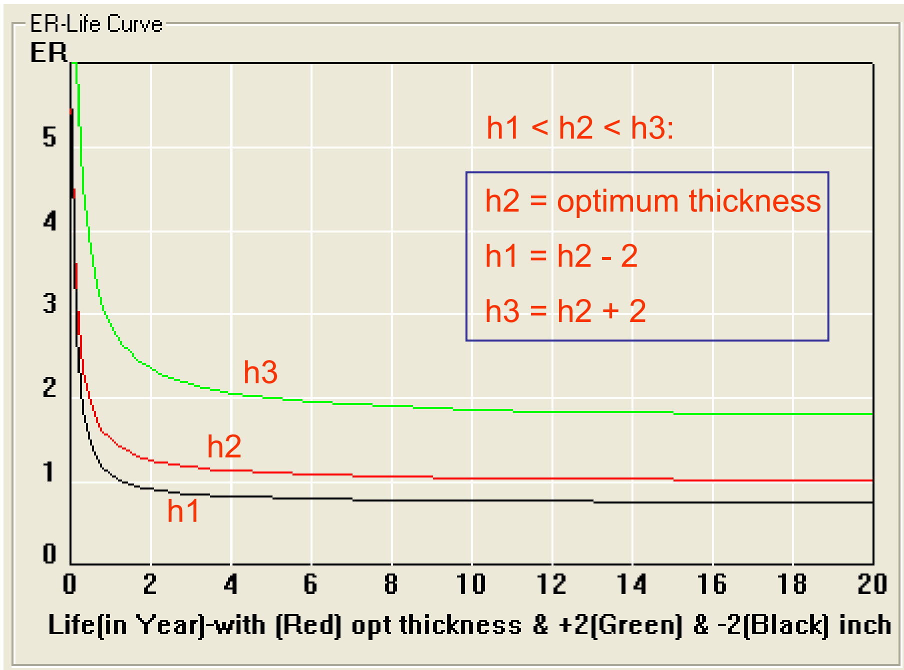
One the user clicks the "optimize" button, the ER-thickness curve will be plotted, as shown in the next figure. Based on this curve, the program searches for the optimum


Pavement Life Calculation
ER Optimization
Calculated ER
1.02
Optimum ER
1.02
Optimize
Optimum Thickness (in)
5.1
The Location of the Maximum Tensile Stress
Layer
X
Y
Z
1
0
0
5.1
Normal Stress (psi)
139.5
139.5
30.3
Pavement Life Curve
Draw
ER-Thickness Curve
ER
Thickness (in inch)
Automatic process for thickness optimization
ER-Life Curve
ER
Stress corresponds to the optimum AC thickness
Life(in Year)-with (Red) opt thickness & +2(Green) & -2(Black) inch
Export Data
Leave Studio

thickness that gives the ER value equal to the minimum required ER. The optimum AC thickness (which is 5.1 inch in the above figure) is then shown in the "Optimum Thickness" field. It can also be seen that the calculated ER (1.02) now is equal to the optimum ER. The outputted maximum tensile stress now corresponds to the optimum AC thickness. The optimization curve also shows the sensitivity of the ER value to the AC thickness.

2.3.3 Pavement Life Calculation

The design tool also provides the option of drawing the ER-pavement life curves. As mentioned earlier, the calculated ER value and the ER-thickness curve correspond to the end of the pavement life. The user can click "Draw" button in upper-right corner of the output window to draw the ER-pavement life curve, from which it can be seen how the ER value changes as the pavement ages. After the "Draw" button is clicked, the program automatically calculated the ER values from the beginning to the end of the pavement life for different pavement thicknesses. The next figure shows the curves drawn in the ER-life frame. The rest information in that window remains the same. Three ER-pavement life curves with different colors were drawn, with each color corresponding to a thickness, as illustrated in the following figure. The red curve also denotes the ER-pavement age variation for the optimum thickness. So, the pavement life calculation cannot be performed before the thickness optimization. Without pushing "optimize" button in the output window, the "Draw" button at the upper-right corner is always disabled. It is also worth mentioning that pavement life curve cannot be drawn for the case when AC material properties are inputted at one time point (which means that in AC layer information input window, the AC properties are not taken as default). In the case, the material properties do no change with time, and the program can only calculate the ER or optimum thickness but the "draw pavement life curve" function is disabled.



2.3.4 Export

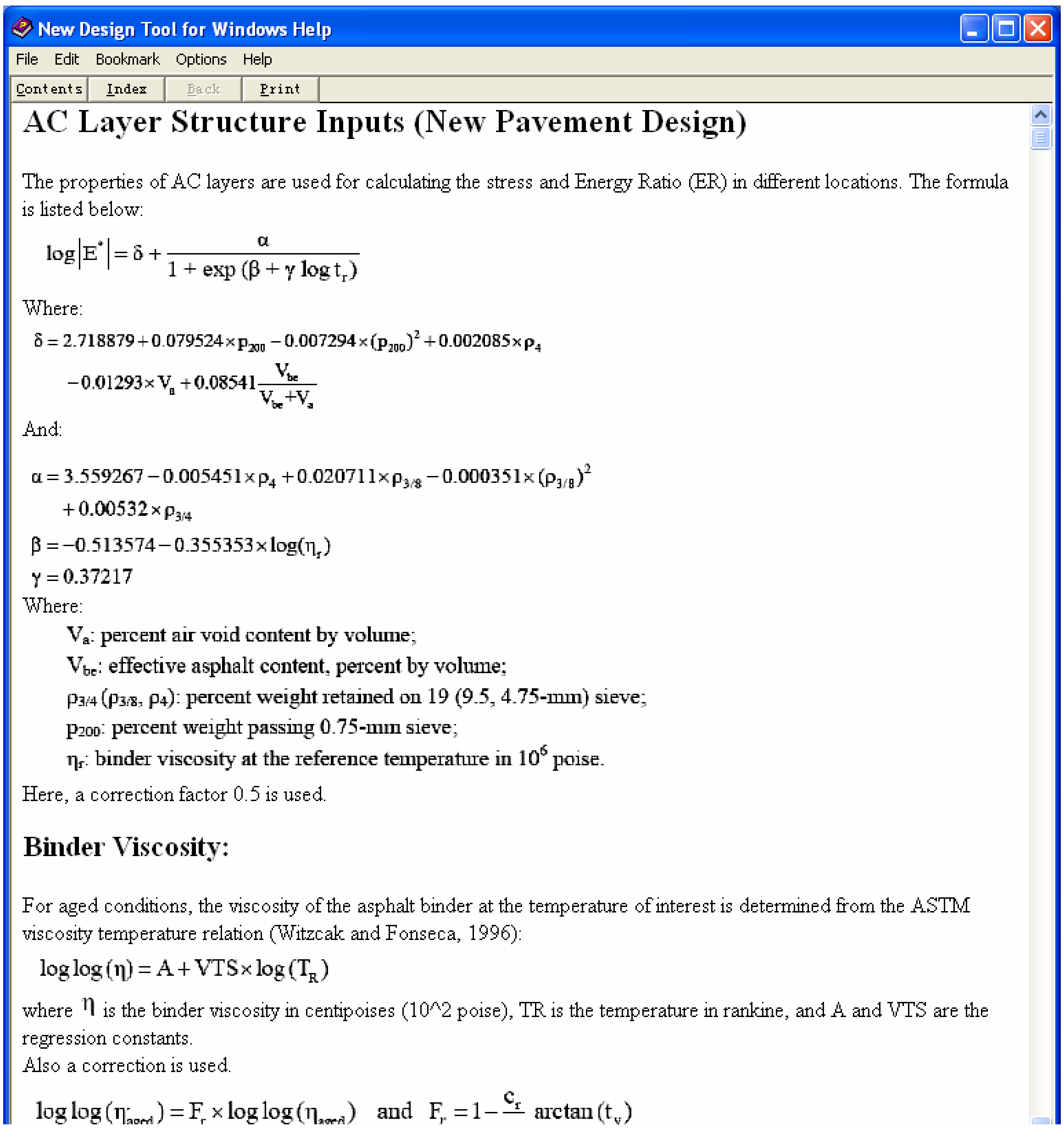
The "Export" function in the output window will allow user the export the results (such as the ER values correspond to the ER-thickness curve and the ER-life curve) into Excel file. At the same time, the input data (including the traffic information, AC properties and structural information, base group information, etc.) will also be summarized in this file.

2.4 Units

This program used English unit if not specified otherwise. The user is not allowed to change the unit from one to another, since the unit is fixed in some calculations.

2.5 HELP

The HELP menu provides Help topics and software information. The user can go the help topics and read the documentation corresponding to each interface. The user can also press F1 to for help at any time when the program is running. For example, when the user is at the "AC Layer" input window, pressing F1 will result in a pop-up window as follows:



AC Layer Structure Inputs (New Pavement Design)

The properties of AC layers are used for calculating the stress and Energy Ratio (ER) in different locations. The formula is listed below:

$$\log|E^*| = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log t_r)}$$

Where:

$$\delta = 2.718879 + 0.079524 \times p_{200} - 0.007294 \times (p_{200})^2 + 0.002085 \times \rho_4 - 0.01293 \times V_a + 0.08541 \frac{V_{be}}{V_{be} + V_a}$$

And:

$$\alpha = 3.559267 - 0.005451 \times \rho_4 + 0.020711 \times \rho_{3/8} - 0.000351 \times (\rho_{3/8})^2 + 0.00532 \times \rho_{3/4}$$

$$\beta = -0.513574 - 0.355353 \times \log(\eta_r)$$

$$\gamma = 0.37217$$

Where:

V_a: percent air void content by volume;
V_{be}: effective asphalt content, percent by volume;
$\rho_{3/4}$ ($\rho_{3/8}$, ρ_4): percent weight retained on 19 (9.5, 4.75-mm) sieve;
p_{200}: percent weight passing 0.75-mm sieve;
η_r: binder viscosity at the reference temperature in 10^6 poise.

Here, a correction factor 0.5 is used.

Binder Viscosity:

For aged conditions, the viscosity of the asphalt binder at the temperature of interest is determined from the ASTM viscosity temperature relation (Witzcak and Fonseca, 1996):

$$\log\log(\eta) = A + VTS \times \log(T_R)$$

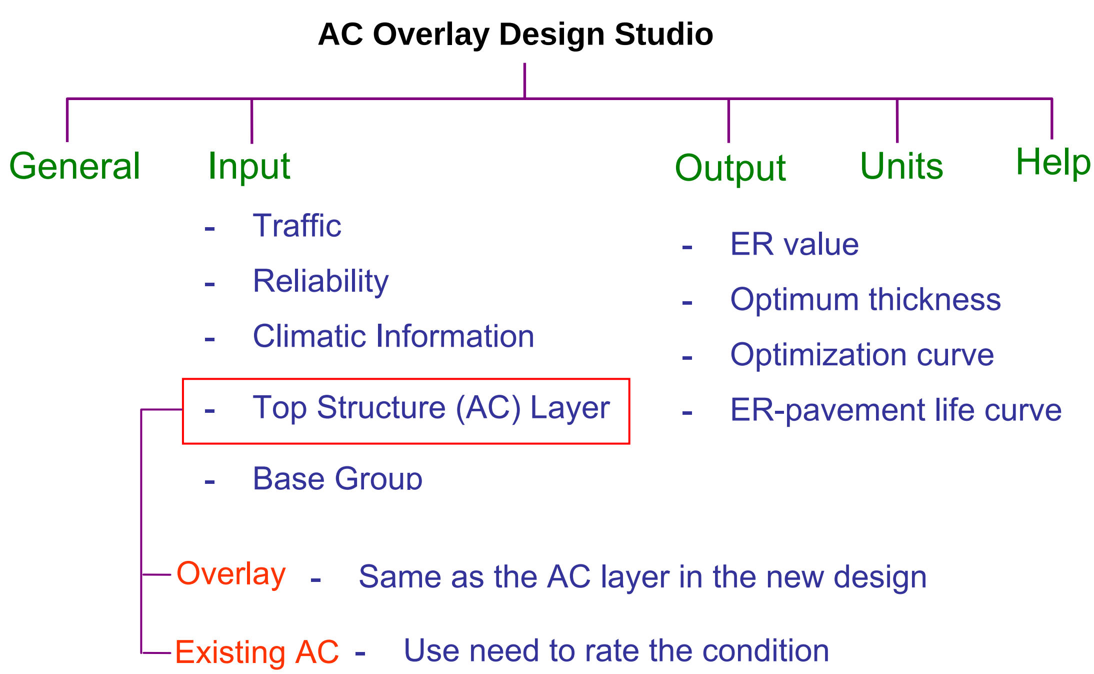
where η is the binder viscosity in centipoises (10^2 poise), TR is the temperature in rankine, and A and VTS are the regression constants.

Also a correction is used.

$$\log\log(\eta'_{aged}) = F_r \times \log\log(\eta_{aged}) \quad \text{and} \quad F_r = 1 - \frac{c_r}{\ } \arctan(t_v)$$

3.0 OVERLAY DESIGN

If "Overlay Design Using Energy Ratio" is selected at the beginning, the software will be doing overlay design. The interface structure for overlay design, illustrated in the following figure, is almost the same as for the new pavement design. The only difference between the New Pavement Design and the Overlay Design is that the top structural layer in the AC overlay design includes two parts: the AC overlay and the existing AC layer. How to deal with the existing AC layer is the only thing that differentiates the AC overlay design from the new pavement design.



3.1 GENERAL

Same as the "New Pavement Design."

3.2 INPUT

3.2.1 Traffic Input

The traffic input for Overlay Design is the same as for New Pavement Design.

3.2.2 Climatic Information

Same as in the New Pavement Design.

3.2.3 Reliability Input

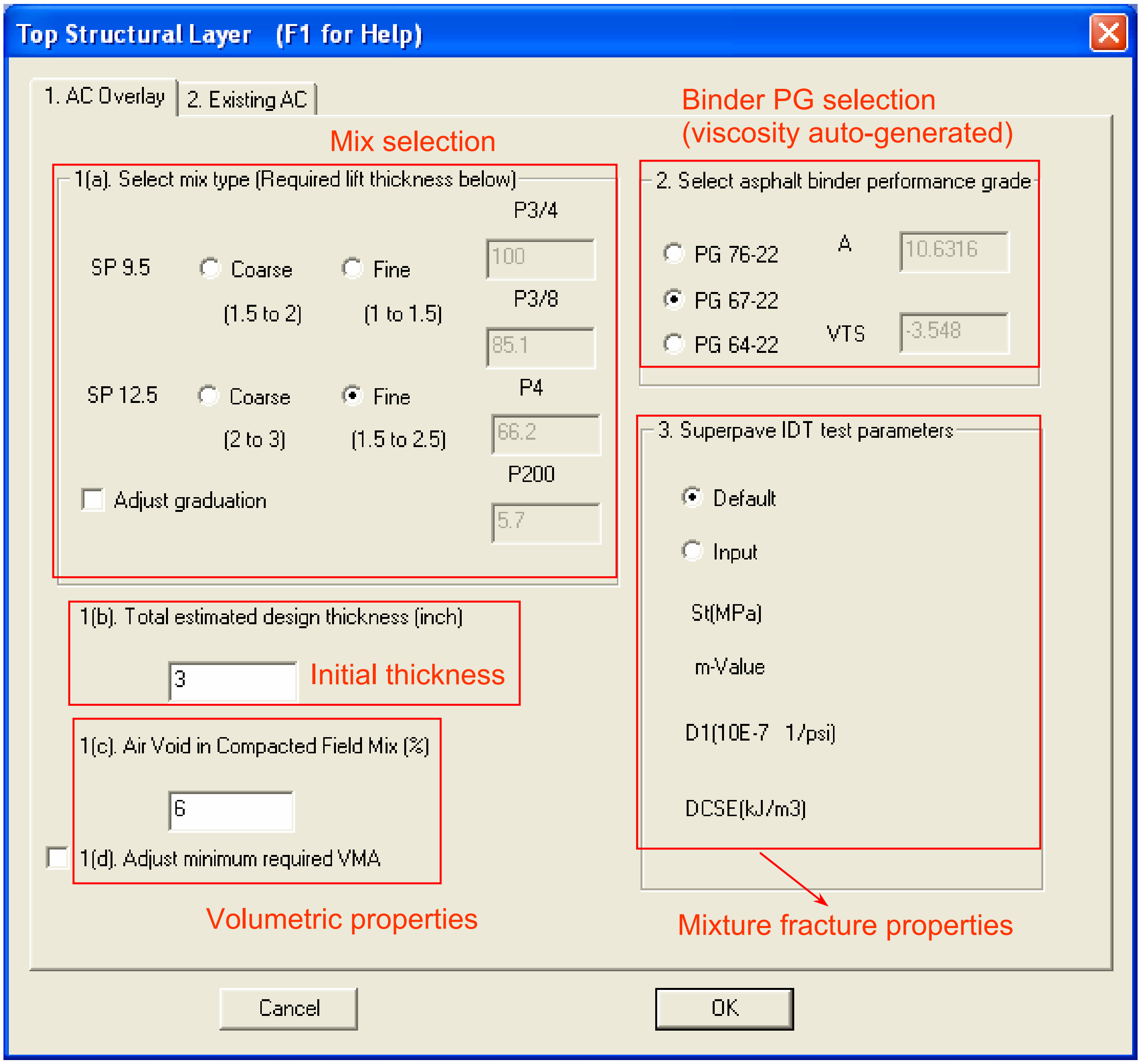
This is similar to that in the New Pavement Design. The only difference is that the reliability requirement in the AC overly design is higher. For example, in the AC overlay design, the reliability levels are 95-99% for limited access, 90-97% for urban arterials, 90-950% for rural arterials and collectors.

3.2.4 Top Structure (AC) Layer

The input menu for the AC layer information in the overlay pavement design includes two input tabs: one for the AC overlay and one of the existing AC layer.

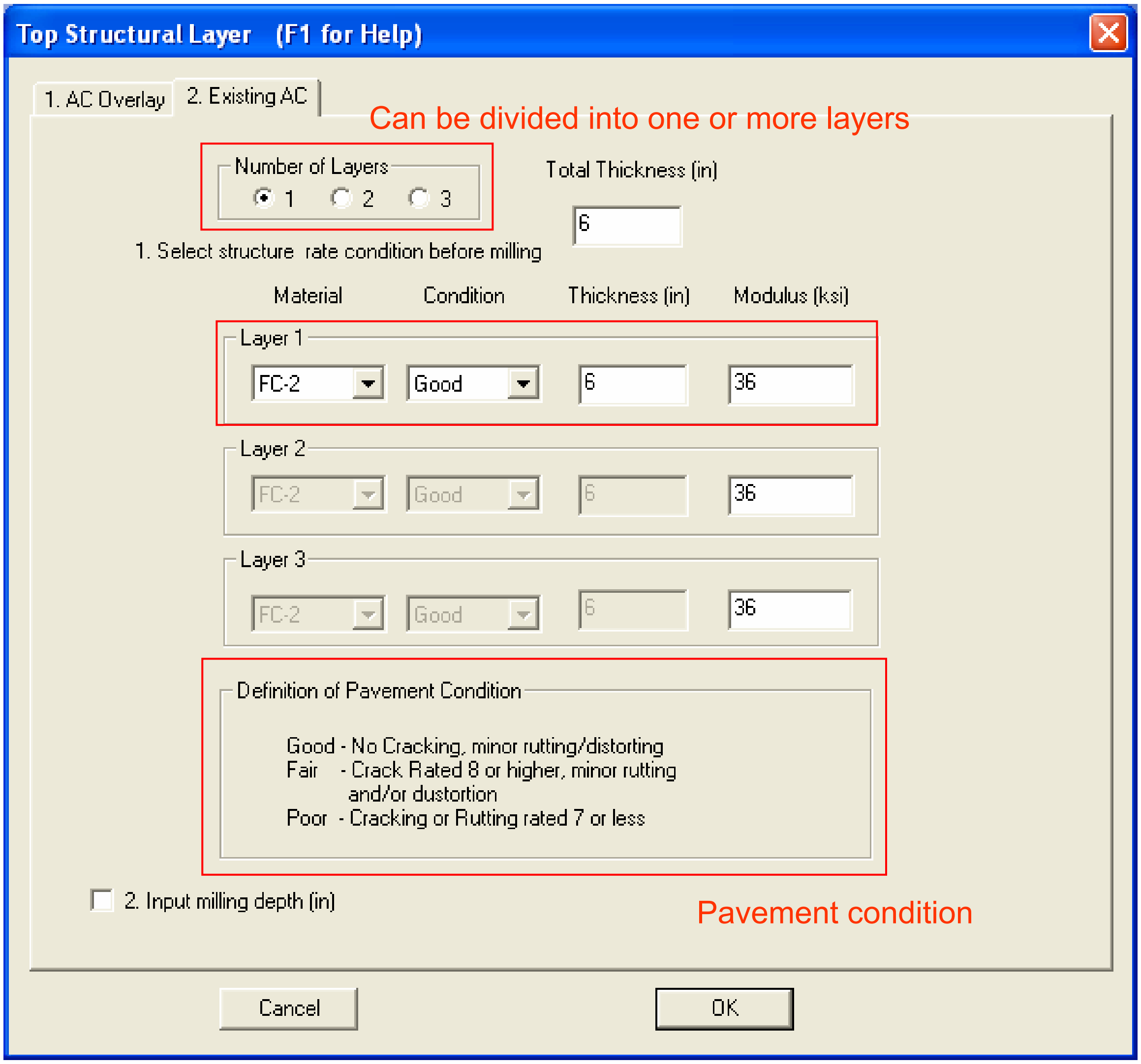
3.2.4.1 AC Overlay

This part is the same as the AC layer in New Pavement Design. In the New Pavement Design, there are multiple tabs for the information of AC layer. In the Overlay Design, the user needs to input all the information for the overlay in one tab as shown in the following figure. The AC overlay part also includes three parts: mix selection and design, binder selection, and mixture properties. The mix and binder selection, and the mixture properties are treated in the same way as in the new Pavement Design. The only difference from the new pavement design is estimated AC layer thickness only include overlay thickness.



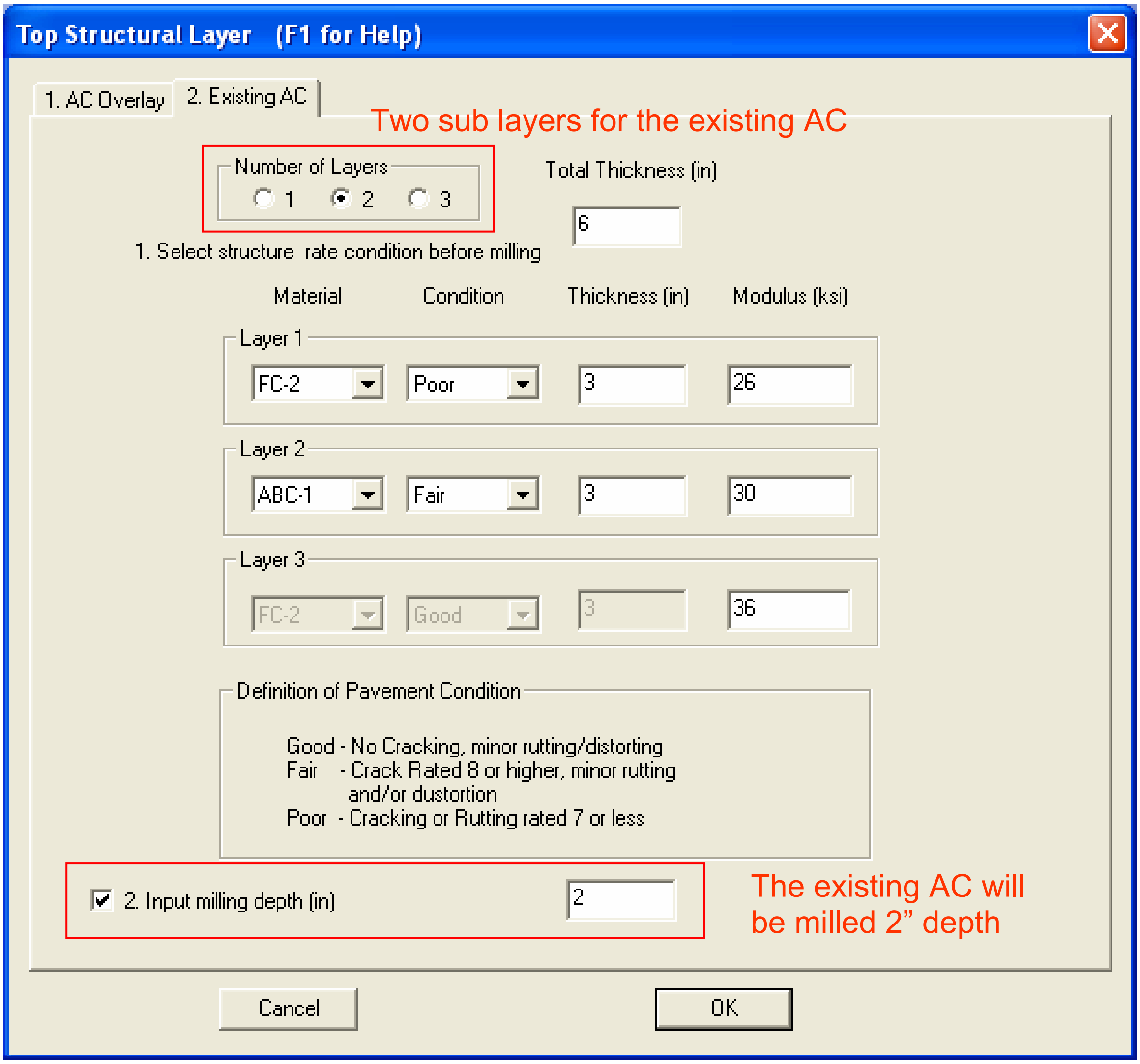
3.2.4.1 Existing AC Layer

For the existing AC layer, the design engineer needs to determine first how many layers will be used to represent the structure, as shown in the following figure. For each layer in the existing AC structure, the user needs to input the selection of material type, the condition (Good, Fair, Poor), and the thickness of the layer. The definition of each pavement condition is also given in the input window. Based on the condition of each layer, the program calculates the layer modulus according to the reduced layer coefficients.



As shown in the second item of the above window, there is a choice of "input milling depth." Based on the condition of each layer, the user needs to determine if it is necessary to do milling. If milling is required, then the checkbox in front of the "Input milling depth" is checked, and the user needs to determine the milling depth. For example, as shown in the following figure, the existing AC structure includes two layers:

the first layer (surface) is FC-2 material under poor condition; the second layer (bottom) layer is ABC-1 material under fair condition. The estimated moduli for the first and second layer are 26 ksi and 30 ksi respectively.



As shown above, two inch of the existing AC layer will be milled. As a result, the effective (existing) AC will only include the remaining one inch of the first layer and the 3-in second layer. Following the method described in the report, the program will calculate equivalent layer modulus and thickness for the existing AC layer after milling.

3.2.5 Base Group

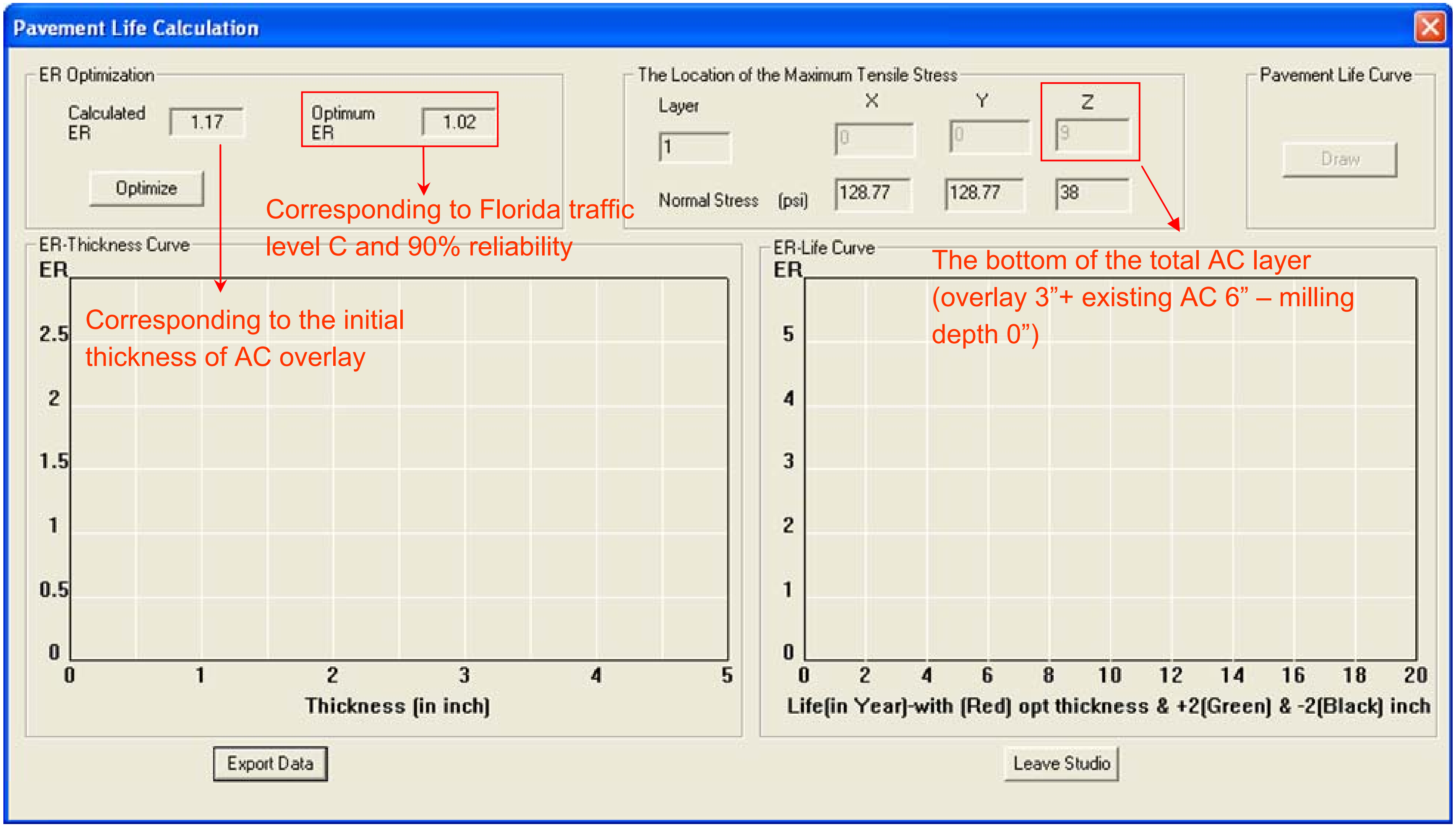
Same as in the New Pavement Design.

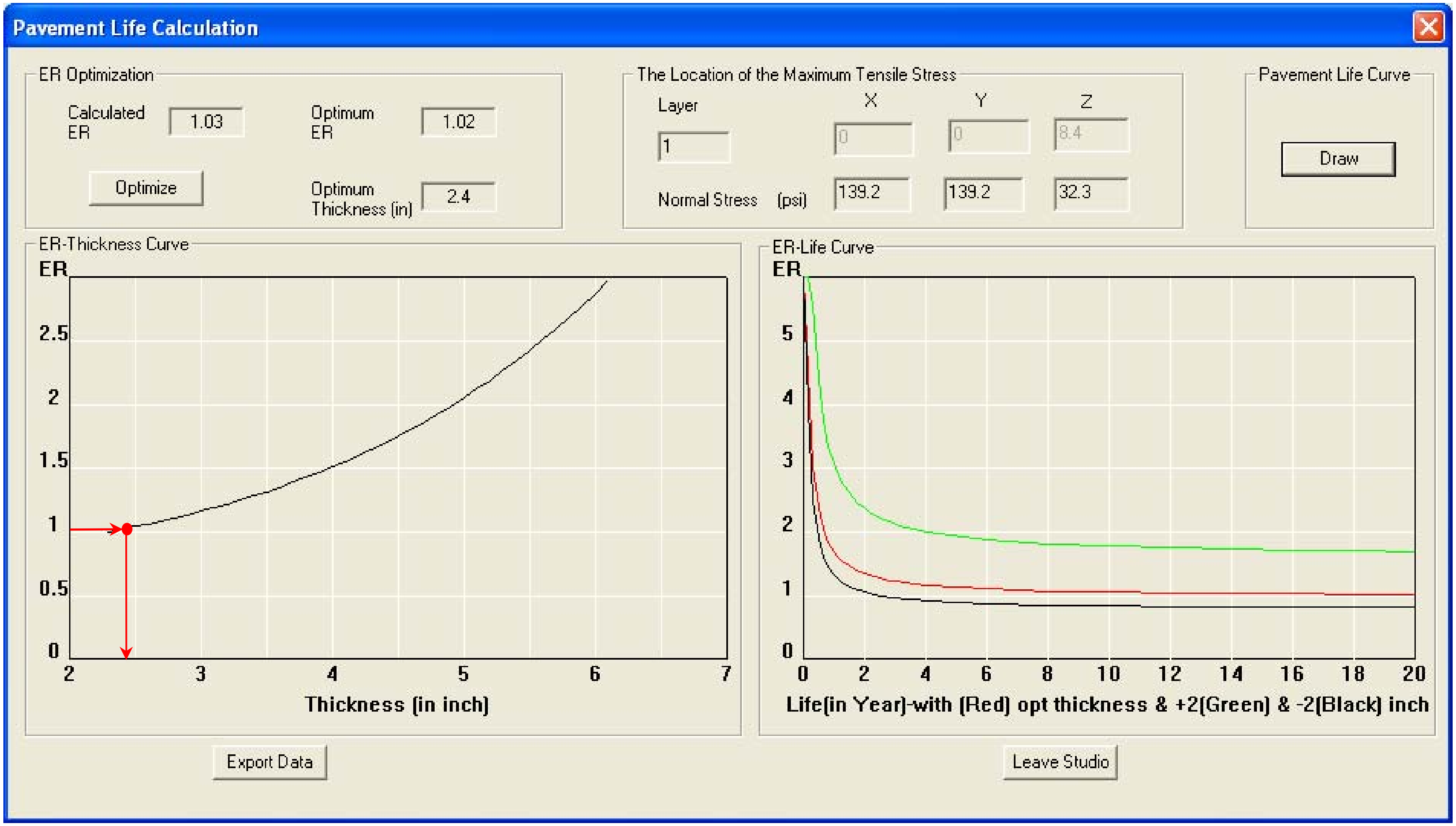
3.3 OUTPUT

The output information and format for the overlay design are the same as the new pavement design, which can be seen from the figures in the next two pages. The first figure shows that the value of calculated ER corresponding to the initial thickness of the AC overlay and the value of the optimum ER are given when the window is popped up. The maximum stress at the bottom of the total AC layer is also given. The thickness of the total AC layer is equal to the thickness of the overlay plus the thickness of the existing AC layer before milling and minus the milling depth.

When the "Optimize" button is pressed, the ER-thickness curve will be drawn. This curve shows the ER value changes with the thickness of the AC overlay, as shown in the second figure below. The optimum thickness will be the thickness corresponding to the optimum ER value, which can be identified from the ER-thickness curve.

After the overlay thickness optimization, the user can click "Draw" button in upper-right corner of the output window to draw the ER-pavement life curve. As shown in the second figure, three ER-pavement life curves with different colors were drawn, with each color corresponding to an overlay thickness. The meaning of each of curve is the same as that in the new pavement design. Detailed explanation is omitted here.


Pavement Life Calculation
ER Optimization
Calculated ER 1.17
Optimum ER 1.02
Optimize
Corresponding to Florida traffic level C and 90% reliability
The Location of the Maximum Tensile Stress
Layer 1
X 0
Y 0
Z 9
Normal Stress (psi) 128.77 128.77 38
Pavement Life Curve
Draw
ER-Thickness Curve
ER
Corresponding to the initial thickness of AC overlay
Thickness (in inch)
ER-Life Curve
ER
The bottom of the total AC layer (overlay 3"+ existing AC 6" – milling depth 0")
Life(in Year)-with (Red) opt thickness & +2(Green) & -2(Black) inch
Export Data
Leave Studio


Pavement Life Calculation
ER Optimization
Calculated ER 1.03
Optimum ER 1.02
Optimize
Optimum Thickness (in) 2.4
The Location of the Maximum Tensile Stress
Layer
X
Y
Z
1
0
0
8.4
Normal Stress (psi)
139.2
139.2
32.3
Pavement Life Curve
Draw
ER-Thickness Curve
ER
2.5
2
1.5
1
0.5
0
2
3
4
5
6
7
Thickness (in inch)
ER-Life Curve
ER
5
4
3
2
1
0
0
2
4
6
8
10
12
14
16
18
20
Life(in Year)-with (Red) opt thickness & +2(Green) & -2(Black) inch
Export Data
Leave Studio