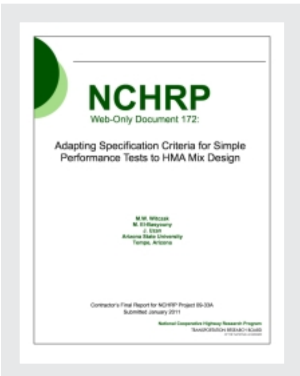

NCHRP
Web-Only Document 172:
Adapting Specification Criteria for Simple Performance Tests to HMA Mix Design

# Adapting Specification Criteria for Simple Performance Tests to HMA Mix Design

## DETAILS

0 pages | null | PAPERBACK
ISBN 978-0-309-43098-2 | DOI 10.17226/22895

## AUTHORS

**ACKNOWLEDGMENT**

This work was sponsored by the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program (NCHRP), which is administered by the Transportation Research Board (TRB) of the National Academies.

# THE NATIONAL ACADEMIES

*Advisers to the Nation on Science, Engineering, and Medicine*

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Charles M. Vest is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both the Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Charles M. Vest are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

**www.national-academies.org**

**Contents**

Page

**List of Figures**

Page

# List of Tables

## 1 INTRODUCTION

Hot mix asphalt (HMA) mix design is usually accomplished after the contractor has been selected and the overall pavement design, including specific layer thicknesses and types, has been defined and finalized. At a minimum, the mix design process ensures that the contractor's materials meet the requisite specifications. However, at this early stage in a project, before construction has begun, the ability to evaluate potential pavement performance and make adjustments to the mix based on its predicted performance in the defined pavement structure is equally important. The Mechanistic-Empirical Pavement Design Guide (1) (MEPDG) is highly recommended for this purpose. However, as 100 runs or more of the MEPDG may be needed to cover the range of possible values of air voids ($V_a$) and binder volumes ($V_b$) associated with a mix design, using the MEPDG may not be the quickest and most efficient way to evaluate the effect of the HMA mix design on pavement performance. More appropriate for this purpose are the closed form solutions of the MEPDG first developed in NCHRP Project 9-19 (1a) as the E* SPT Specification Criteria Program (1b) and then used in NCHRP Project 9-22 (2) as the basis for the Quality-Related Specification Software (QRSS). These solutions permit rapid, reliable prediction of pavement performance within programs coded in Microsoft Excel spreadsheets.

## 2 OBJECTIVE

The objective of NCHRP Project 9-33A, "Adapting SPT Specification Criteria to HMA Mix Design," was to develop a software program for evaluating the potential performance of HMA mix designs in combination with their intended pavement structures. This *Program for Integrated Analysis of HMA Mix And Structural Designs* is coded as a Microsoft Excel spreadsheet (*9-33A(Sep10).xlsm*) and supporting files (2a).

The program incorporates the MEPDG spreadsheet solutions developed in NCHRP Projects 9-19 and 9-22. Predictions of permanent deformation (rutting) and fatigue cracking are made on the basis of the estimated HMA dynamic modulus, $E^*$; thermal cracking predictions are based on estimates of the HMA creep compliance, $D$.

The program will serve as a multi-purpose tool for HMA mix and structural design engineers. First, it provides an easy graphical check that a prospective job mix formula (JMF) falls within the acceptable limits of air voids and effective binder volume established by the project's HMA specification. Second, using powerful, pre-solved solutions of the MEPDG, it provides rapid estimates of the performance of the JMF over the design life of the HMA pavement and whether the JMF will satisfy specific pavement distress criteria established by the agency. Third, it can test "what-if" scenarios by estimating how changes in the JMF, pavement structure, or both may affect performance. Finally, it can be used in forensic investigations of pavement distresses, by assessing the potential contributions of the HMA and pavement structure to distress development before any testing is conducted.

This report presents

1. a description of the program's inputs and outputs,

2. a brief review of the underlying performance prediction models, and
3. examples illustrating the use of the program to analyze specific mix-structure combinations.

Technical familiarity with the MEPDG design principles (1), the E* SPT Specification Criteria Program (1b), and the QRSS (2) will enhance the user's understanding of the program.

## 3 SYSTEM SUPPORT AND PROGRAM INPUTS

The program is coded in Microsoft Excel (2007 Version) with Visual Basic Application support. To run the program properly, the user's computer requires the following system capabilities:

1. Microsoft Excel 2007 or higher: Neither Excel 2003 nor the utility for converting Excel 2003 files to Excel 2007 or higher format will run the program due to its size and complexity.
2. Solver Function: The program uses the Solver function to complete the iteration process in the rutting and fatigue cracking modules. To check if your Excel program already has this function, open Excel and go to the "Data" tab. The "Solver" function is located under the "Analysis" category in the far right side of the menu. If it is missing, install it through the following steps:
    a. Press the "Office" button at the upper-left corner of the Excel program
    b. Select "Excel Options" at the bottom.
    c. Press the "Add-Ins" on the left side of the window.
    d. Press the "Go" button with the selection of "Excel Add-Ins" in the manage category.
    e. In the pop-up "Add-Ins" window, check "Solver Add-in".
    f. Press "OK".

The program has three main sections organized as a series of worksheets:

1. The first worksheet (Program Welcome Screen [Figure 1]) presents the program title and information on the program authors.
2. The second and third worksheets (User Input 1 [Figure 2] and Main Input Screen) provide for the main user inputs.
3. The remaining worksheets are charts presenting the program output.

The required program inputs include (1) general project information, (2) traffic, climatic, structural, and job mix formula (JMF) data, and (3) distress criteria. Figure 2 shows the general program input screen.

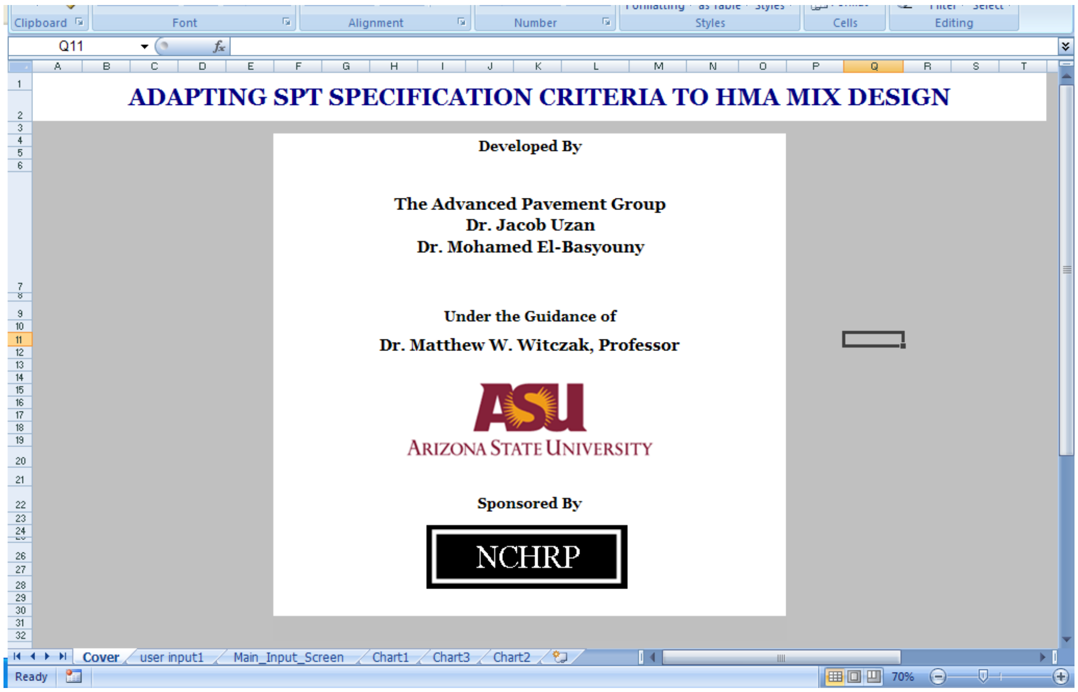



**Figure 1. Program Welcome Screen**

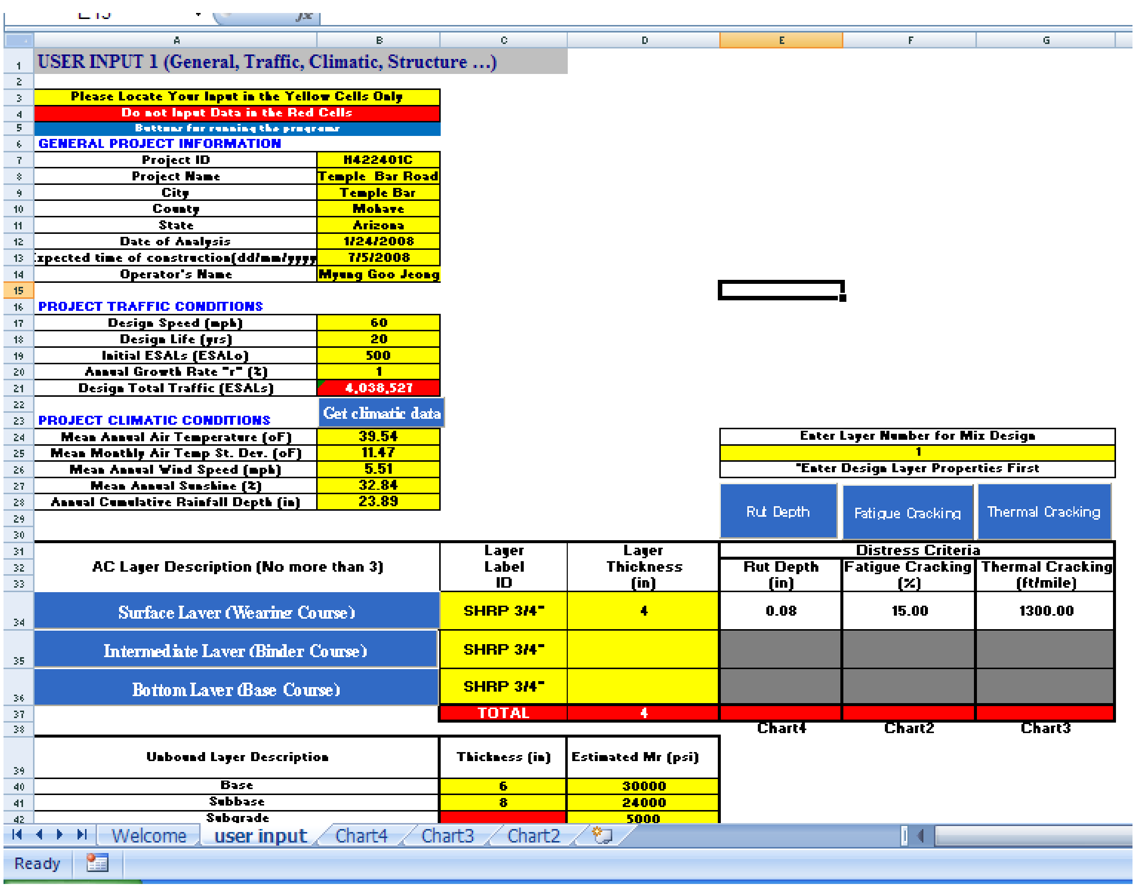



**Figure 2. Program Input Screen**

The purpose of the program is to assess certain parameters of the HMA mix design in relation to the intended performance of the HMA mix in the pavement structure. Thus, the program focuses solely on the three major HMA distress types: (1) permanent deformation (rutting), (2) classical bottom-up fatigue cracking, and (3) thermal cracking. The program does not consider other HMA distresses such as moisture damage or those distresses related to defects in the pavement structure, such as shear deformation in unbound layers materials, seasonal frost effects, etc.

Cells in the program input screen (Figure 2) are color coded as follows:

- Yellow indicates a user input cell that requires the user to enter information.
- Red indicates a cell used by the program to calculate a parameter. The user should not alter or input any value in this cell.
- Blue (which may appear in some cases as Light Gray) indicates a button that, when clicked, will open another window for additional user inputs.
- Dark Gray indicates an inactive cell.

**3.1 General Inputs**

General inputs are project information relating to:

- Project ID
- Project name
- City
- County
- State
- Date of analysis
- Date of construction
- Operator's Name

These inputs provide project identification but are not critical to the program analysis. Only the "Date of Construction" will influence the program output and that to a minor degree.

**3.2 Traffic Inputs**

The traffic inputs required by the program are an estimate of the design vehicle speed, design life, initial daily ESALs, and ESAL growth rate. The daily ESALs represent the design traffic in one direction on the critical design lane. The program will automatically calculate the total design ESALs for the entire design life of the pavement. It should be noted that a damage analysis is not done for each axle type or load, as is the procedure in the more sophisticated MEPDG analysis. Rather, all traffic is handled in terms of the widely accepted and known *E18KSAL* (equivalent 18 kip single axle [wheel] load) methodology.

### 3.3 Climatic Inputs

There are two options for inputting climatic information. The first option is to click on the “Get Climatic Data” button, which will allow the user to select from among 900 different weather stations from across the 50 United States. This option will also allow the user to interpolate among up to 6 different weather stations based on the longitude, latitude, and elevation of the project site. The climatic temperature file created by the program is identical with the climatic file created by the MEPDG and can be used interchangeably between the two programs. Figure 3 shows the climatic input screen with a portion of the list of the available weather stations.

Selecting a weather station from this list causes the program to automatically calculate the following parameters from the selected weather data:

- Mean annual air temperature
- Mean monthly air temperature standard deviation
- Mean annual wind speed
- Mean annual sunshine
- Annual cumulative rainfall depth

These parameters are required to solve for the rut depth and fatigue cracking effective temperature equations used by the program.

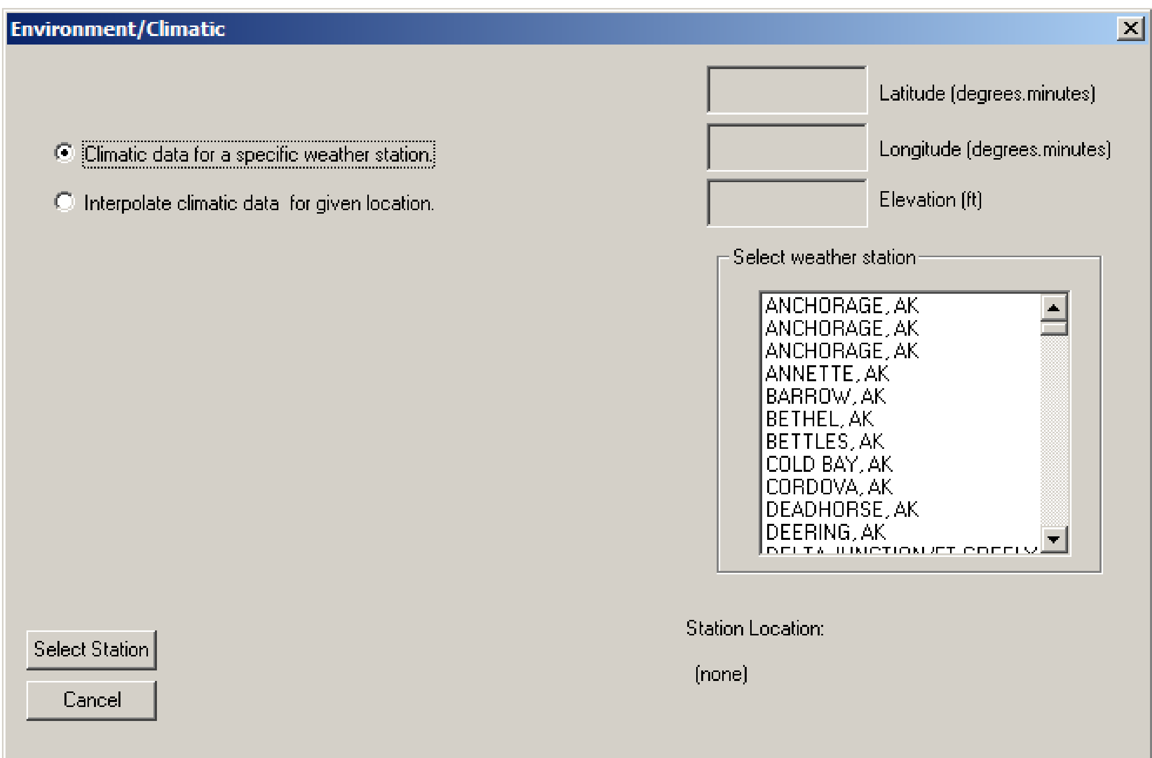



**Figure 3. Climatic Input Screen**

The second climatic input option is to manually enter the climatic data listed above in the appropriate cells in the user input worksheet. If not all of this information is known, the user can elect to use the first option and then manually enter those parameters that are known.

The second option is the minimum required if only rutting, fatigue cracking, or both are considered in the analysis. However, if the analysis includes thermal cracking, the first option is mandatory as it will create an hourly temperature file needed for the thermal cracking analysis.

### 3.4 Structural Inputs

The structural inputs required for this program are (1) the thickness of all pavement layers (HMA, chemically stabilized, or unbound granular) and (2) the moduli of all non-asphaltic base, subbase, and subgrade layers. While the non-asphaltic mixture layers are not overly important to the prediction of the rutting and thermal cracking of the HMA layers, they are very important to the accurate prediction of the fatigue cracking of any HMA layer. The program accepts information for up to three different HMA courses (Surface/Wearing, Intermediate/Binder and Bottom/Base).

### 3.5 JMF Design Inputs

The mix design inputs are the key inputs of the program since all calculations are based on them. Clicking on the blue button for a specific HMA layer will open its input screen. However, before the user clicks on the HMA layer for the analysis, the layer number must be entered in cell “E25”. Entering this layer number instructs the program to use its layer properties in the analysis. The analysis evaluates the expected rut depth in each HMA layer, while fatigue cracking is determined only for the bottommost HMA layer and thermal cracking only for the topmost HMA layer. This analytical approach is identical to the methodology used in the MEPDG.

The input screen for the HMA layer properties has five different tabs as seen in Figure 4. The asphalt binder grade (performance grade [PG], viscosity grade [AC], or penetration grade[Pen]) is selected and its specific gravity entered are entered in the tab labeled “Material Properties.” The asphalt content by weight and the target air voids ($V_a$) for each HMA layer are also entered in this tab. Finally, aggregate properties such as the maximum and nominal aggregate sizes and the aggregate bulk and effective specific gravities are entered in the tab.

The aggregate gradation by sieve size is entered in the tab labeled “JMF Gradation.” Four sieve sizes (3/4”, 3/8”, #4, and #200) are the minimum required sieves to be inputted as they are the sieve sizes used by the Witczak Predictive Equation (2b)within the program to estimate dynamic modulus values for the HMA layers.

The tab labeled “Mix Design Specifications” permits selection from among the 38 different mix specifications available in the program. These thirty-eight include five different Superpave specifications for different aggregate sizes (3), 30 different Asphalt Institute specifications for different air voids and aggregate sizes (4), North Dakota

DOT's 0.5-inch class 29, Australian Association of Asphalt Pavement's 9.5mm specification, and New Brunswick DOT's 9.5 mm Type D specification. The Superpave specifications were obtained from the Asphalt Institute SP-2 publications (3, 4) and may not reflect the most up to date Superpave specification.

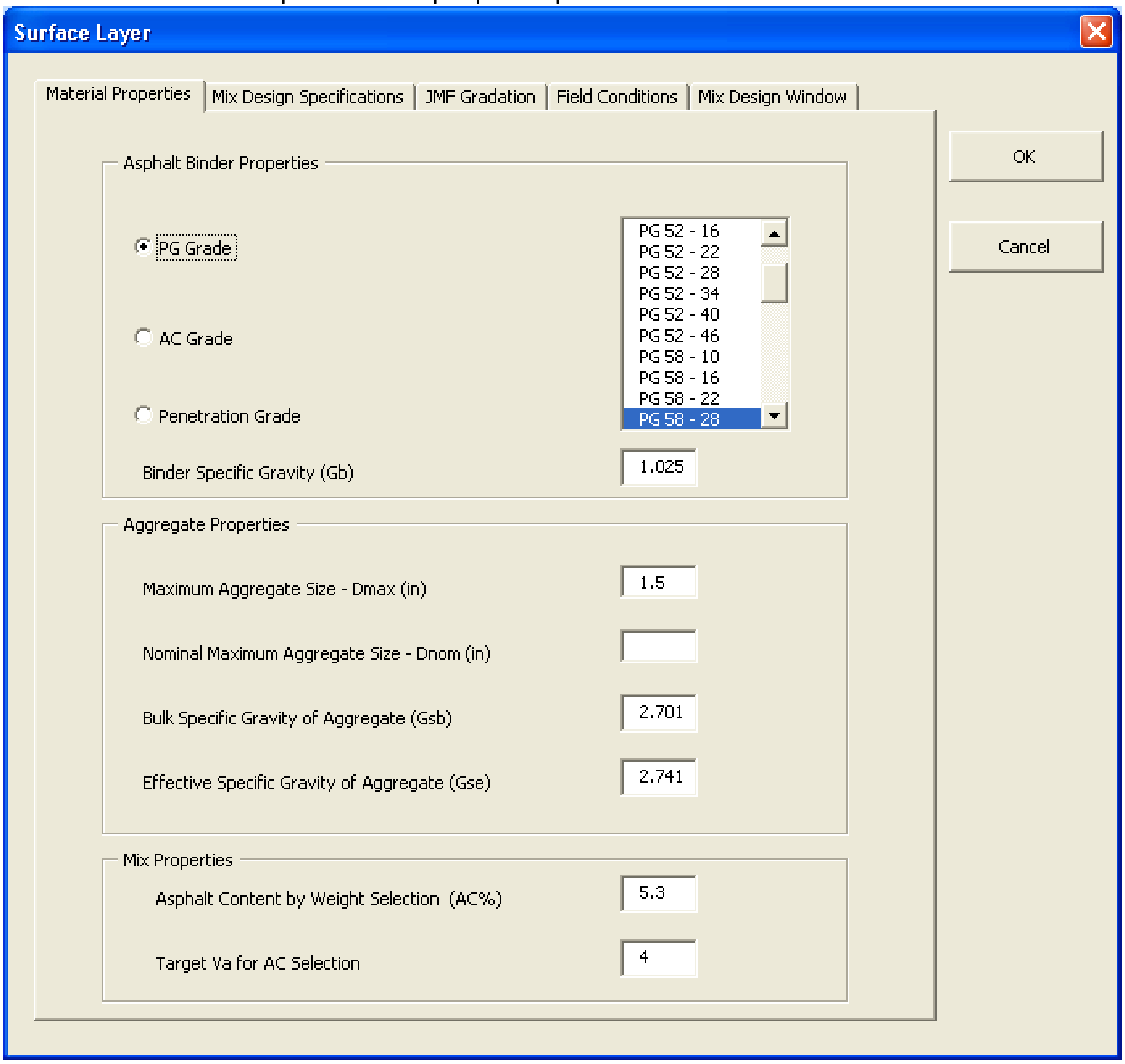
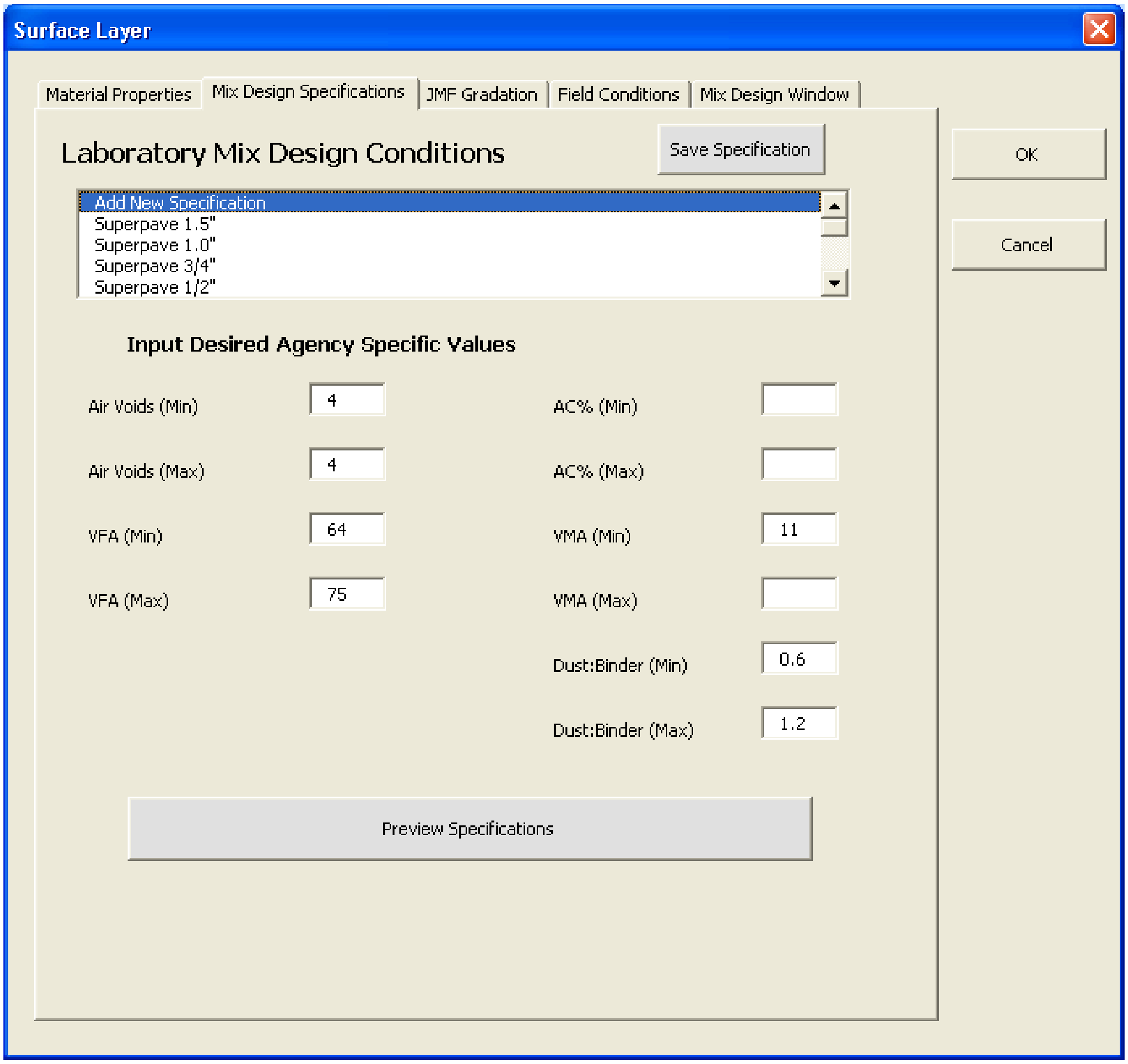


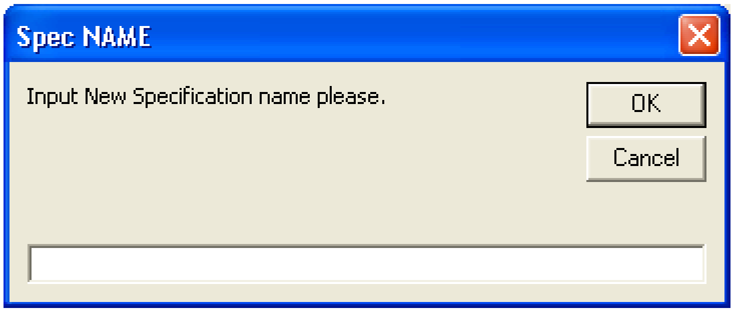

**Figure 4. Asphalt Material Properties Input screen**

A key attribute of the "Mix Design Specifications" tab is the capability to input any other agency specification by selecting "Add New Specification." This allows the entry of different volumetric specification parameters in the program's specification library. Clicking on the "Save Specification" button allows naming of the new specification and saving it to the list of available specifications, as seen in Figure 5b. The number of new specifications that an agency can add is limited only by the number of available columns in Microsoft Excel.

Clicking on the "Preview Specifications" button launches a tab labeled "Specification Window" that shows a plot of laboratory JMF air voids (%) versus the effective volume of the asphalt binder ($V_{beff}$) with an overlaid acceptance window derived from the specification limits (Figure 6). This acceptance window identifies the space within which any $V_a$-$V_{beff}$ point will meet the specification. This visual approach is helpful in quickly identifying a mix design that properly conforms to the volumetric requirements of the mix specification. This "window of acceptability" concept was first introduced in the literature by McLeod (4a) and later refined by Coree [4b]. Figure 6 shows a specification limits plot.




a) Mix Specification Input Screen




b) New Specification Name Input

**Figure 5. Mix Design Specification Input Screen**

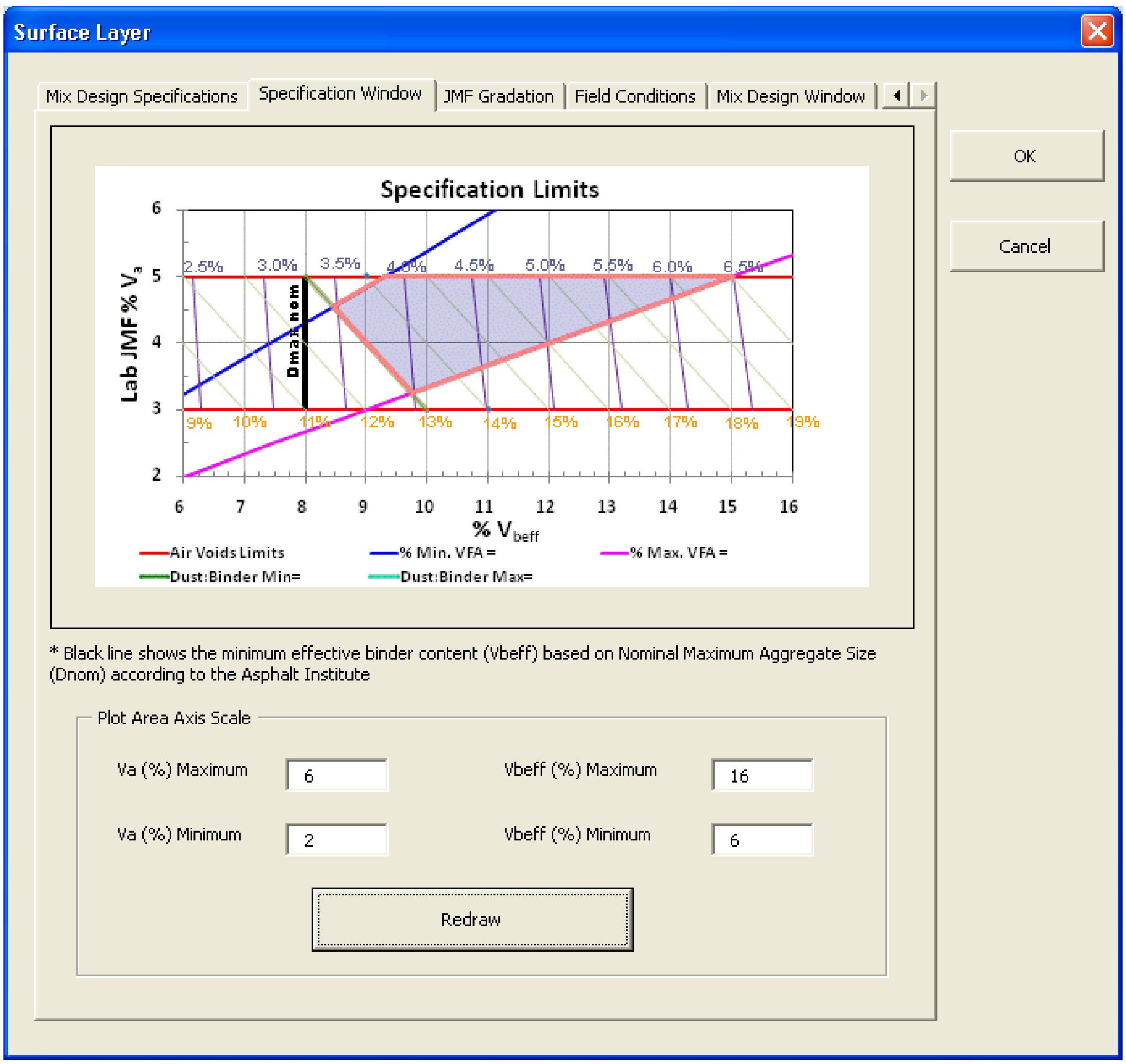



**Figure 6. Specification Limits Plot**

As stated above, the JMF aggregate gradation is entered in the tab labeled "JMF Gradation" in terms of percent passing each sieve size. Figure 7 shows the JMF gradation input screen. The bold sieve sizes are the minimum sieve sizes required to conduct the analysis. The remaining sieve sizes are for purposes of information and documentation only.

The tab labeled "Field Conditions" allows entry of the expected in-situ project conditions, and, in particular, the values of the field control air voids or relative compaction. As shown in Figure 8, the required inputs to this tab are the in-situ target air voids, the air voids limits in the field, and the construction tolerance on the binder content. Based on the in-situ air voids and the JMF properties, an in-situ effective binder volume ($V_{beff}$%) will be calculated and presented in the screen. (The target asphalt content (AC%) is a copy of the value that was input in the "Materials Properties" tab.) The in-situ $V_{beff}$ is calculated by the following equations:

$$v_{beff} = \frac{\left[P_b - (100 * G_b * (G_{se} - G_{sb}) / (G_{sb} * G_{se}))\right] * G_{mb}}{G_b} \quad (1a)$$

$$G_{mb} = \frac{100 - V_a}{\frac{100 - P_b}{G_{se}} + \frac{P_b}{G_b}} \quad (1b)$$

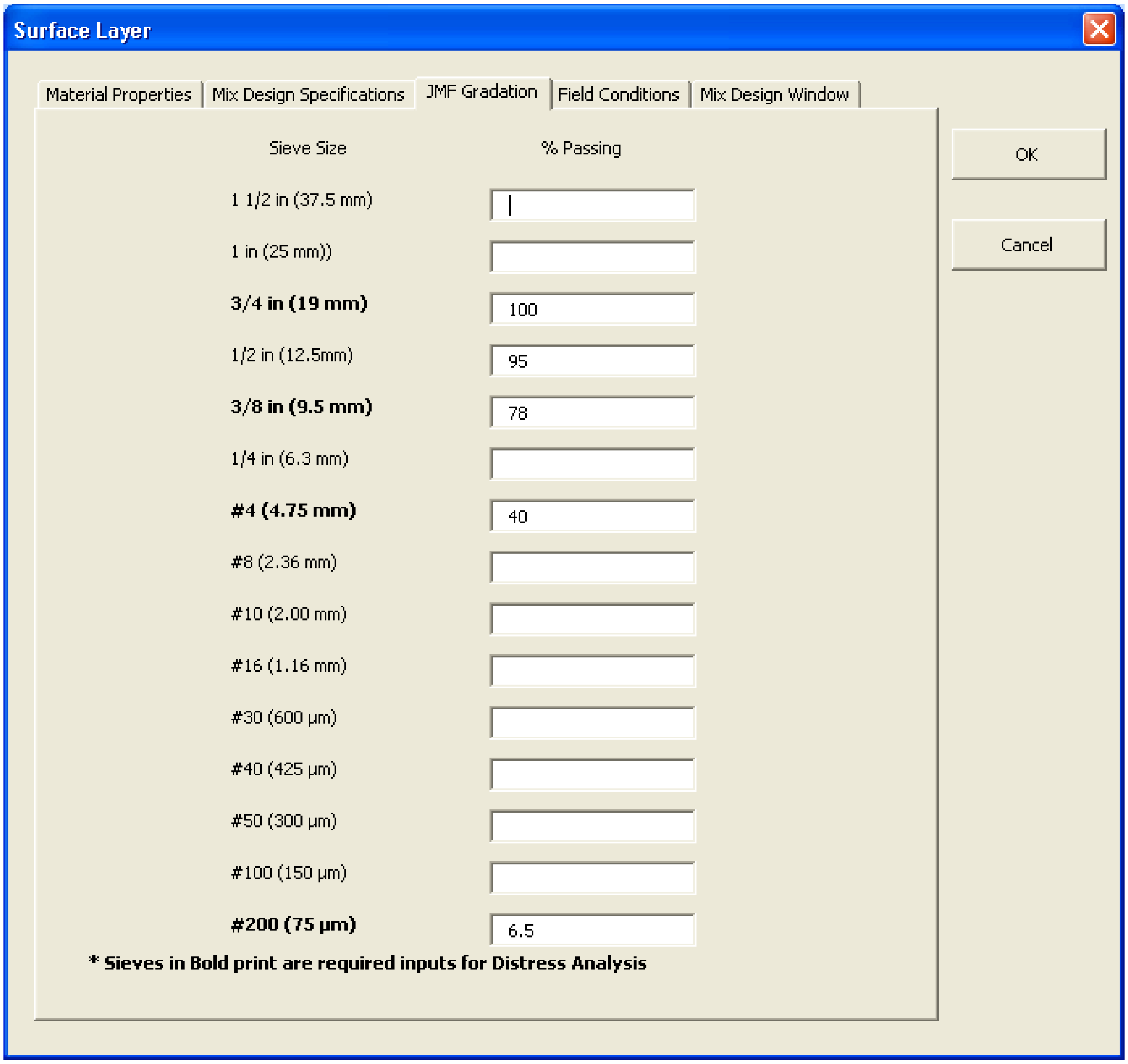



**Figure 7. JMF Gradation Input Screen**

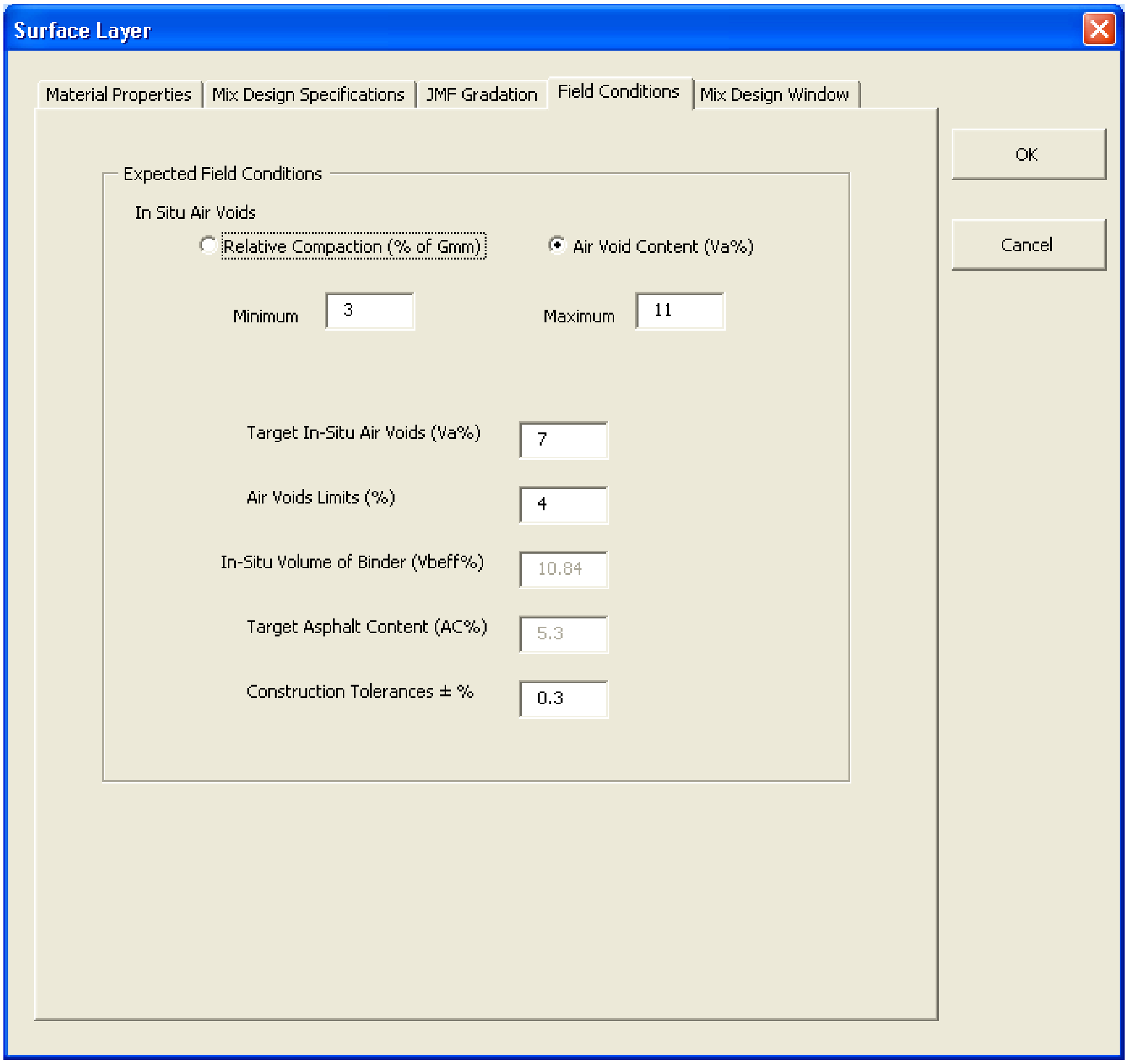



**Figure 8. Expected Field Conditions Input Screen**

The final tab is labeled "Mix Design Window" and presents the validation of the JMF as shown in Figure 9. Figure 9 plots the JMF laboratory air voids versus its effective binder volume similar to the Specification Limits plot in Figure 6. The grey area bounded by red is the acceptance range for the JMF mix design based on the selected specification. The coordinates of the filled red circle within the acceptance range is the $V_a$-$V_{beff}$ combination determined for the JMF mix design used in the analysis; the dashed line is the acceptance range of effective binder volume based on the construction tolerance entered in the "Field Conditions" tab. If the JMF mix design under analysis lies inside the window, as it does in Figure 9, then the mix design satisfies the specification selected by the agency. However, if the JMF mix design lies outside the acceptance window, the binder content must be adjusted in the "Material Properties" tab and the analysis rerun until a mix design is obtained that lies within the acceptance window.

Another important option provided in this tab is that of checking the box that selects the use of the Asphalt Institute's minimum $V_{beff}$ criterion, which is a function of the maximum aggregate size (Dmax). If this option is selected, the acceptance window will be modified by imposing a minimum value of $V_{beff}$ as seen in Figure 10. Note the difference in the left side limit of the acceptance window in Figure 10 compared to that in Figure 9 where the Asphalt Institute's minimum $V_{beff}$ criteria was not selected. For a ¾-inch Dmax the minimum $V_{beff}$ is 9%, which is reflected in the mix design acceptance window. (In the plot the term "JMF S-L" denotes a surface layer JMF while the intermediate layer (binder course) is indicated by "I-L" and the bottom layer (base course) by "B-L.")

The use of the Asphalt Institute's $V_{beff}$ criterion is recommended regardless of what specification is followed. This criterion is, in reality, a VMA (Voids in Mineral Aggregate) criterion that does an excellent job of ensuring that the mix design provides the minimum asphalt content necessary to achieve desirable HMA mixtures.

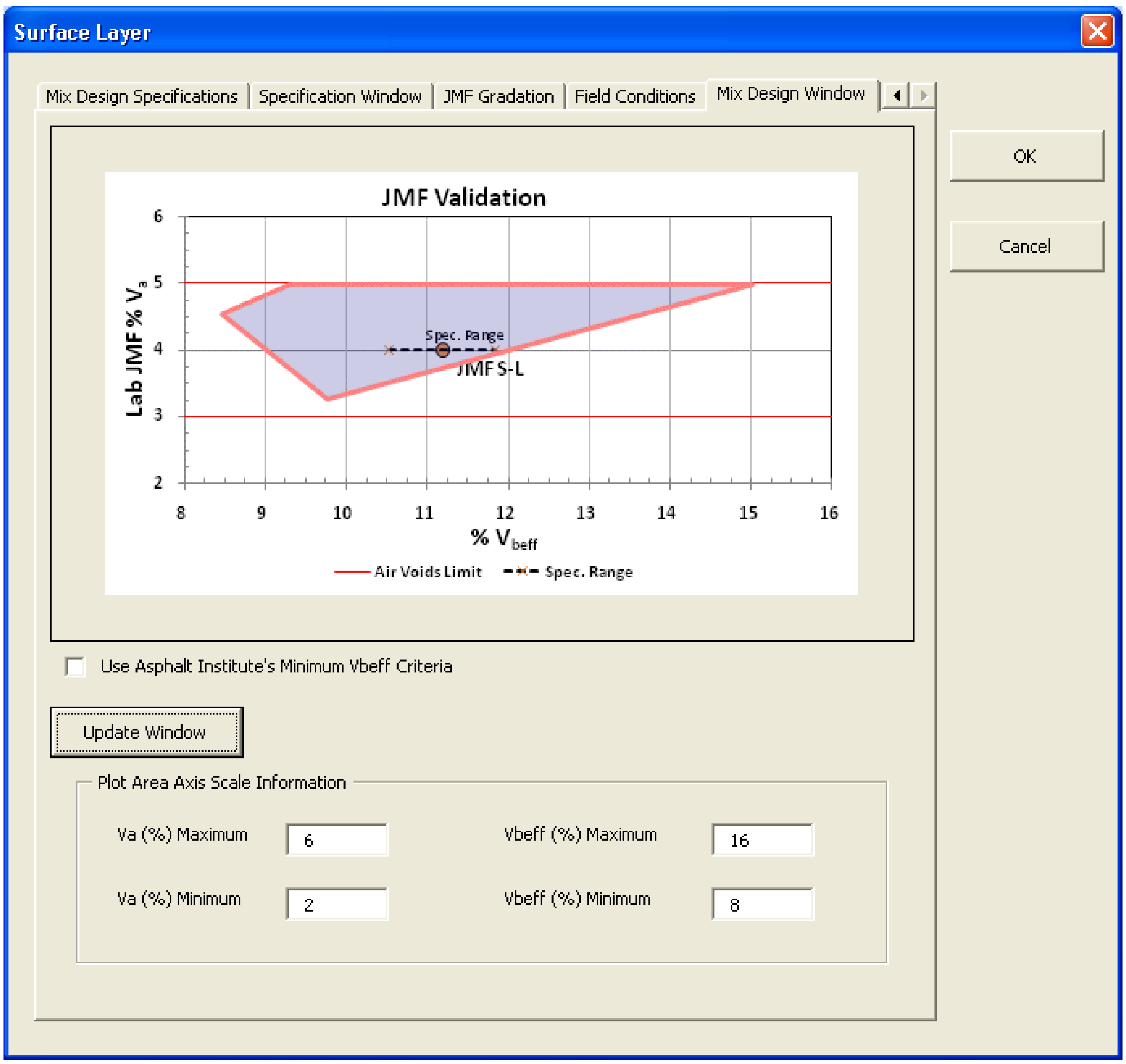



**Figure 9. Mix Design Window**

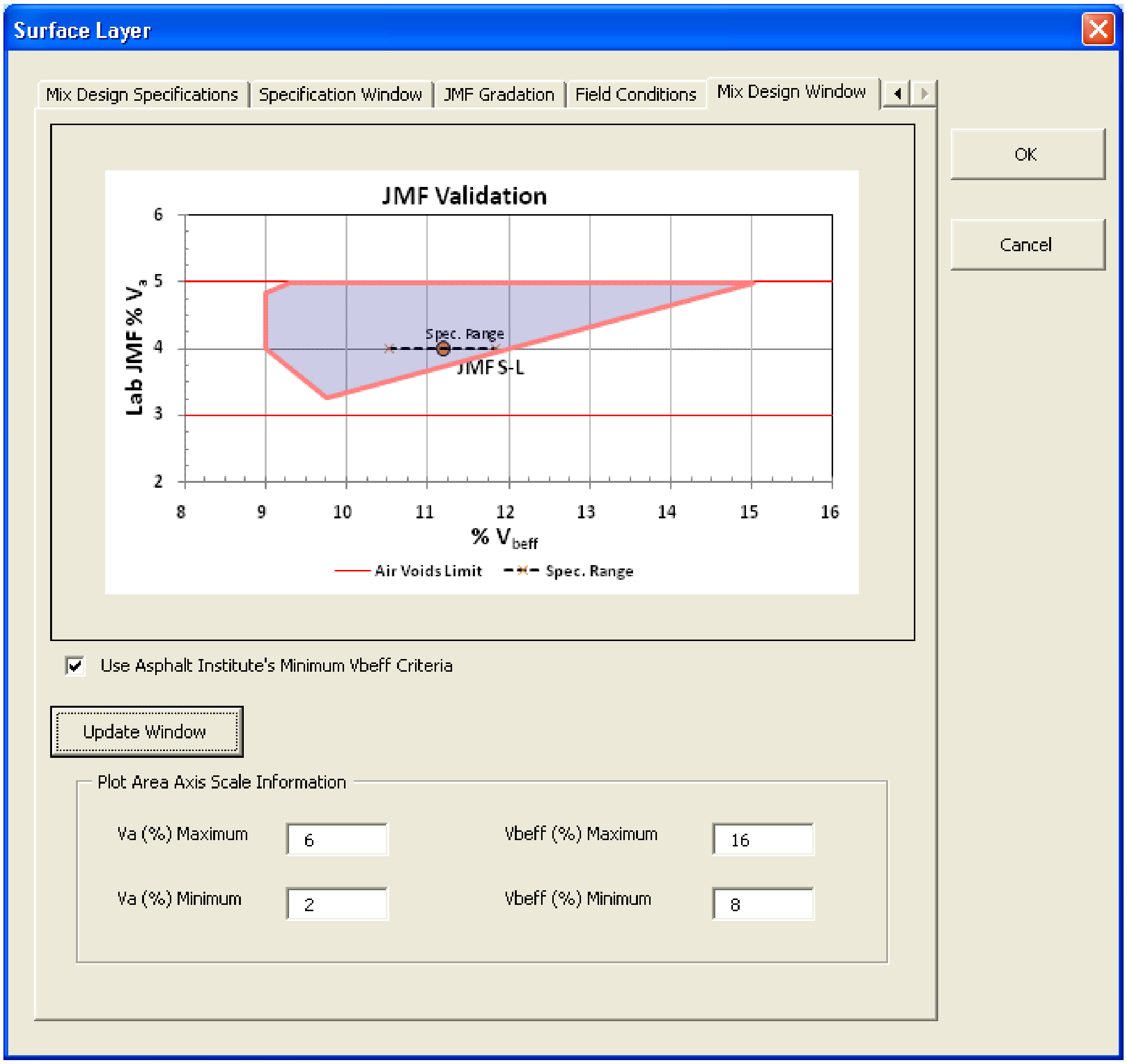



**Figure 10. Use of Asphalt Institute Min $V_{beff}$ Criteria - Mix Design Window**

The program analyzes one asphalt layer at a time, and the number of the layer to be analyzed is entered in "User Input" cell E25. However, for the rutting analysis the JMFs for the other layers are also needed. For these other layers, only the information in the "Material Properties," "JMF Gradation," and "Field Conditions" tabs is needed and only these tabs will be displayed for data entry. Figure 11 shows an example of the Mix Design Screen for the intermediate HMA layer. Clicking "Use Same Properties as Design Layer" will instruct the program to use the same aggregate properties as for the design layer.

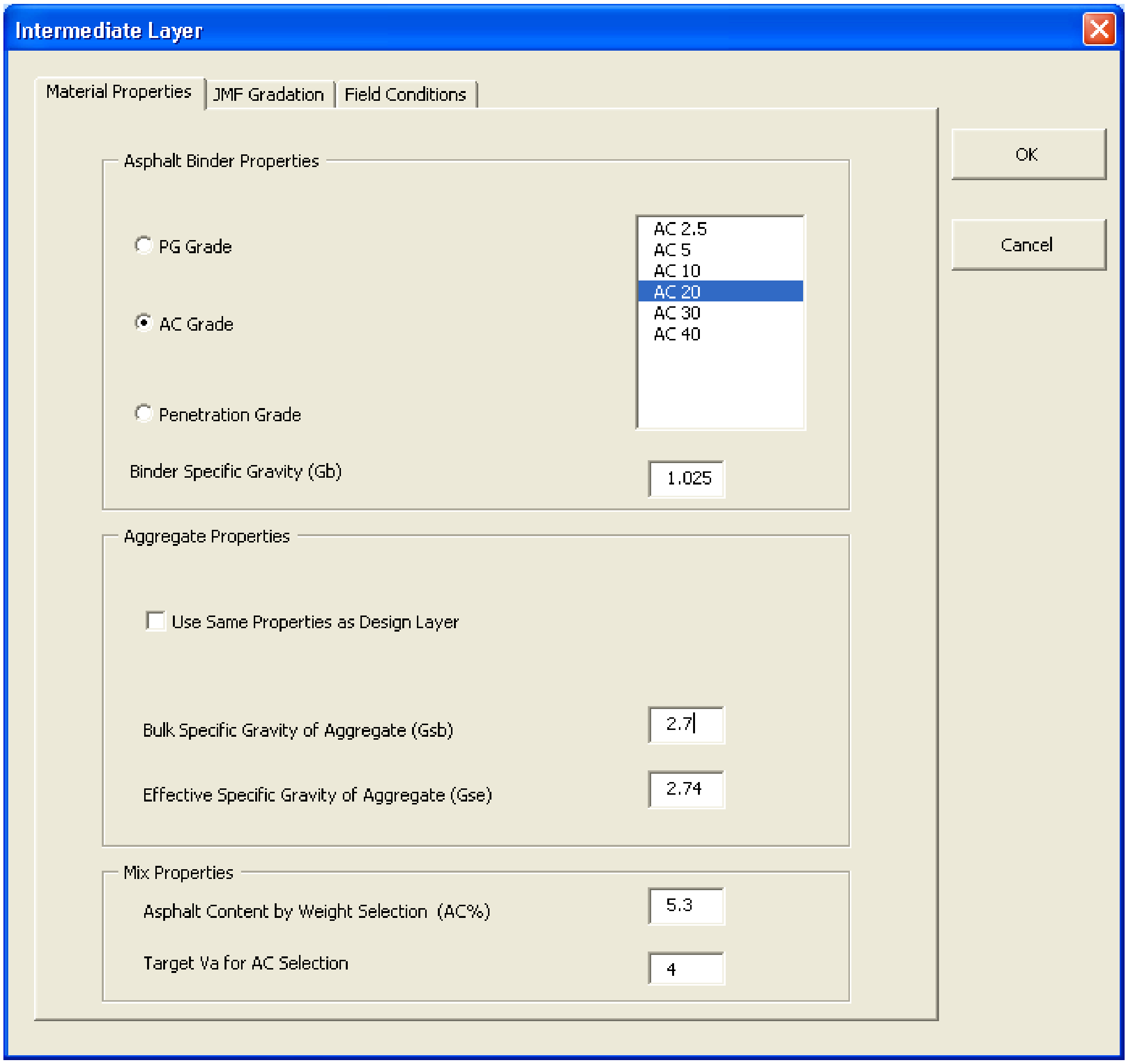



**Figure 11. Non-Analysis Layer Mix Design Window**

### 3.6 Distress Criteria

The final inputs required for the analysis are the pavement distress criteria to which the predicted distresses for the specified combination of mix and structural designs will be compared. Typically, the recommended distress criteria are those distress values that will trigger major maintenance or rehabilitation to the pavement. Figure 12 shows the distress criteria that were entered from the User Input screen shown in Figure 2.

The three distresses analyzed by the program are the permanent deformation (rutting) of each HMA layer in inches, the fatigue cracking in the bottom HMA layer in percent of the lane area cracked, and the thermal cracking in the top HMA layer in feet of cracking per mile. Based on the layer selected for analysis the corresponding distress will be highlighted, as shown in Figure 12 a, b and c.

| Enter Layer Number for Mix Design |
|---|
| 1 |
| *Enter Design Layer Properties First |

Rut Depth | Fatigue Cracking | Thermal Cracking

| Layer Thickness (in) | Distress Criteria | | |
|---|---|---|---|
| | Rut Depth (in) | Fatigue Cracking (%) | Thermal Cracking (ft/mile) |
| 3 | 0.08 | 15.00 | 1300.00 |
| 5 | | | |
| | | | |
| 8 | | | 2112.00 |

a) Analysis Layer 1

| Enter Layer Number for Mix Design |
|---|
| 2 |
| *Enter Design Layer Properties First |

Rut Depth | Fatigue Cracking | Thermal Cracking

| Layer Thickness (in) | Distress Criteria | | |
|---|---|---|---|
| | Rut Depth (in) | Fatigue Cracking (%) | Thermal Cracking (ft/mile) |
| 3 | | | |
| 5 | 0.10 | 20.00 | |
| | | | |
| 8 | | | 2112.00 |

b) Analysis Layer 2

| Enter Layer Number for Mix Design |
|---|
| 3 |
| *Enter Design Layer Properties First |

Rut Depth | Fatigue Cracking | Thermal Cracking

| Layer Thickness (in) | Distress Criteria | | |
|---|---|---|---|
| | Rut Depth (in) | Fatigue Cracking (%) | Thermal Cracking (ft/mile) |
| 2 | | | |
| 3 | | | |
| 4 | 6.00 | 15.00 | |
| 9 | | | 2112.00 |

c) Analysis Layer 3

**Figure 12. Distress Criteria input**

### 3.7 Executing the Program

To analyze the predicted performance of a particular HMA layer, the layer number (1, 2, or 3) is entered in cell E25 below "Enter Layer Number for Mix Design." The analysis is then executed by pressing the blue button (labeled Rut Depth, Fatigue Cracking, and Thermal Cracking) for each distress. Once the analysis is completed, the program provides a separate output chart for each distress. In the case where analysis of another layer is desired, for example, an analysis of the surface layer after that of the intermediate layer is completed, the designer must return to the surface layer material properties screen to update the program with the properties of the surface layer before running its distress analysis.

### 3.8 Output Charts

The output of the program consists of contour line plots of *in situ* air voids ($V_a$) versus effective binder volume ($V_{beff}$) for several levels of the predicted distress (i.e., permanent deformation [rutting], fatigue cracking, or thermal cracking). Figure 13 is an example of the output chart for fatigue cracking. It is important to note that these output plots differ from the mix design window (Figure 10) because the mix design window is based on the JMF laboratory air voids while the output plots are based on the in-situ air voids.

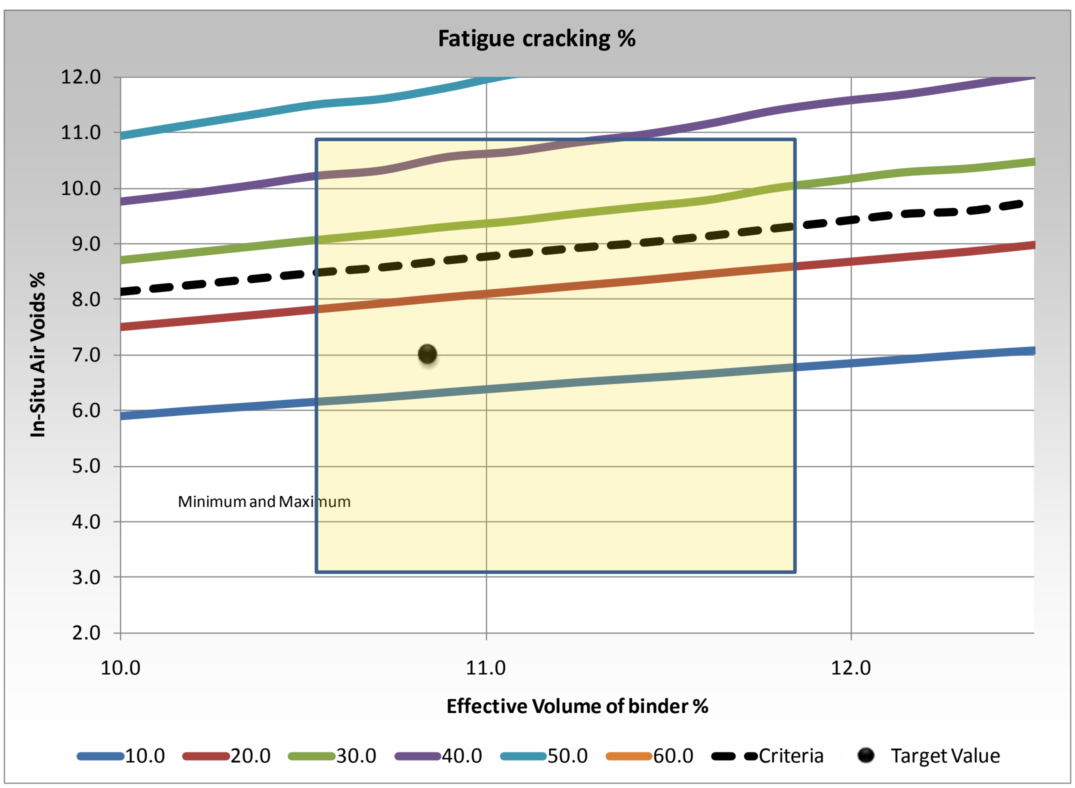



**Figure 13. Output Chart for Fatigue Cracking.**

In Figure 13, the yellow window is delineated by (1) the minimum and maximum in-situ air voids (calculated from the target in-situ air voids ± air voids limits) and (2) the effective binder volume calculated (with Equation 1) from the selected binder content (by weight) ± the construction tolerance. The black dashed line represents the contour line for the distress criterion, which is the agency's maximum value of allowable distress. The black dot representing the target mix design is also shown in the figure. Any target value within the yellow window is accepted from the viewpoint of the mix design specification. However, if this target value is higher than the distress criterion line then it does not satisfy the agency's allowable distress from the viewpoint of predicted performance.

The following Section 4 presents a detailed explanation of the methodology used to predict the distresses shown in these output plots. More details on the output charts will be given in the examples in Section 5.

## 4 DISTRESS PREDICTION MODELS

This section discusses each of the three distresses (permanent deformation [rutting], fatigue cracking, and thermal cracking) and their prediction models in the program.

### 4.1 Permanent Deformation (Rutting) Model

The permanent deformation (rutting) model is based on 864 runs of the MEPDG program conducted by Sotil (5). Since Sotil used early versions of the MEPDG code, new runs were conducted in this project with the latest Version 1.1 of the MEPDG software (5a). The 864 runs of the MEPDG were based on a matrix of climatic, material, traffic, and structural properties including:

- Twelve specific, varying climatic sites covering the continental United States and Alaska (see Table 1)
- Two binder grades: a soft binder, PG 52-34, and a stiff binder, PG 82-10
- Four vehicle speeds: 0.5, 15, 45 and 60 mph, and
- Nine HMA layer thicknesses, ranging from 1 to 20 inches, with the HMA layer further divided into sublayers per Table 2.

All 864 runs were made with the same HMA aggregate gradation (percent retained on the ¾-inch sieve [$rp_{34}$]=0, percent retained on the 3/8-inch sieve [$rp_{38}$]=26.8, percent retained on the #4 sieve [$rp_4$]=46.41, and percent passing the #200 sieve [$pp_{200}$]=8.24), air voids ($V_a$=7 %), and effective binder volume ($V_{beff}$=10 %). This decision was based on the fact that the effects of gradation and volumetric properties on the HMA modulus are small compared to that of temperature, frequency of loading, and binder performance.

A single subgrade-foundation modulus of 14,500 psi was used. This decision was based on the results of previous studies indicating that the effect on HMA rutting of granular layers and foundation underlying the HMA layers is very small, on the order of 3 to 10%.

One traffic level of 10 million E18KSAL repetitions was used, on the basis that the rut depth is proportional to $N^{0.479}$.

The HMA layer rut depth is summed from sublayer contributions. A database of 3552 rut depth contributions was initially stored in the spreadsheet for rut depth predictions.

The original spreadsheet solution developed by Sotil (5) employs a relatively time-consuming interpolation of the stored database. The approach implemented here is different in that the rut depth contribution of each sublayer is fitted with power laws of effective temperature, effective HMA modulus, and vehicle speed, and only the power law coefficients are stored for subsequent prediction of the rut depth.

*4.1.1 Parameter Definitions*

The effective temperature ($T_{eff}$) is composed of two parts. The first part is related to environmental conditions while the second part adds the effects of vehicle speed and the depth of the layer. $T_{eff}$ for rutting is defined as:

$$\begin{aligned} T_{eff} &= 14.620215 - 3.360755 \cdot Ln(Freq_{eff}) - 10.940235 \cdot z + T_f \\ T_f &= 1.209179(MAAT) + 1.717910(\sigma_{MAAT}) - 0.430529(Wind) \\ &\quad + 0.332597(Sunshine) + 0.080086(Rain) \end{aligned} \quad (2)$$

Where:
$T_{eff}$ = modified Witczak effective temperature for rutting, °F
$Freq_{eff}$ = effective loading frequency, Hz
z = desired pavement depth, inches
MAAT = mean annual air temperature, °F
$\sigma_{MAAT}$ = standard deviation of the mean monthly air temperature
Wind = mean annual wind speed, mph
Sunshine = mean annual sunshine percentage, %
Rain = cumulative annual rainfall depth, inches

The effective modulus of the HMA is computed using the latest version of the Witczak Predictive Equation:

$$LogE_{eff} = -1.249937 + 0.029232(pp_{200}) - 0.001767(pp_{200})^2 - 0.002841(rp_4)$$
$$-0.058097(Va) - 0.8022\frac{Vb_{eff}}{(Vb_{eff} + Va)}$$
$$+\frac{3.87197 - 0.0021(rp_4) + 0.003958(rp_{38}) - 0.000017(rp_{38})^2 + 0.00547(rp_{34})}{1 + e^{(-0.603313 - 0.31335\log(f) - 0.383532\log(\eta))}} \quad (3a)$$

Where:
E= HMA dynamic modulus in $10^5$ psi
η= bitumen viscosity in $10^6$ poise (at any temperature and degree of aging)
f = load frequency in Hz
$V_a$ = % air voids in the mix by volume
$Vb_{eff}$ = % effective bitumen content by volume
$rp_{34}$ = % retained on the ¾ inch sieve, by total aggregate weight (cumulative)
$rp_{38}$ = % retained on the 3/8-inch sieve, by total aggregate weight (cumulative)
$rp_4$ = % retained on the No. 4 sieve, by total aggregate weight (cumulative)
$pp_{200}$ = % passing the No. 200 sieve, by total aggregate weight

The bitumen viscosity is computed using the following relationship:
$\log \log \eta = A + VTS \log T_{effR}$ (3b)
where:
η = binder Viscosity in cp
$T_{effR}$ = effective temperature in degrees Rankine

$T_{eff}$ and $E_{eff}$ are mutually dependent variables through the frequency term in Equation 2 since $T_{eff}$ depends on the frequency which in turn depends on $E_{eff}$. Therefore the computation of the rut depth requires the solution of nonlinear equations.

**Table 1. Summary of 12 Selected Environmental Sites for E* Criteria Development**

| Location | MAAT (F) | Wind Speed (mph) | Sunshine (%) | Rainfall (inches) | $\sigma_{MMAT}$ (°F) |
|---|---|---|---|---|---|
| Kotzebue, Alaska | 23.4 | 9.9 | 39.4 | 11.0 | 20.6 |
| Homer, Alaska | 39.8 | 5.5 | 33.4 | 24.7 | 11.2 |
| Grand Forks, ND | 40.1 | 9.0 | 53.8 | 19.5 | 21.6 |
| Great Falls, Montana | 45.0 | 9.9 | 62.1 | 12.8 | 15.6 |
| Chicago, Illinois | 50.5 | 8.1 | 37.1 | 29.8 | 17.2 |
| Hartford, Connecticut | 51.4 | 5.8 | 58.2 | 43.3 | 15.8 |
| Indianapolis, Indiana | 53.3 | 8.3 | 37.2 | 40.4 | 16.4 |
| Oklahoma City, OK | 60.2 | 9.7 | 48.4 | 30.9 | 15.6 |
| Jackson, Mississippi | 64.2 | 4.7 | 66.7 | 51.5 | 12.6 |
| Houston, Texas | 68.8 | 5.9 | 38.0 | 47.5 | 11.2 |

| | | | | | |
|---|---|---|---|---|---|
| Phoenix, Arizona | 74.7 | 5.3 | 60.8 | 6.6 | 14.8 |
| Key West, Florida | 77.7 | 8.4 | 72.6 | 36.8 | 5.6 |

**Table 2. HMA layer thicknesses and sublayering**

| HMA layer thickness, inch | Sublayer thickness, inch |
|---|---|
| 1 | 1 |
| 2 | 1+1 |
| 2.75 | 1+1.75 |
| 3 | 1+1+1 |
| 4 | 1+1+1+1 |
| 6 | 1+1+1+1+2 |
| 8 | 1+1+1+1+2+2 |
| 12 | 1+1+1+1+2+2+4 |
| 20 | 1+1+1+1+2+2+12 |
| Total number of sublayers | 37 |

### *4.1.2 Interpolation Scheme in the NCHRP Project 9-22 Spreadsheet Solution for Rutting Prediction*

The original interpolation scheme used to predict rut depth is described by Sotil (5) and includes the following steps:

1. The results of 3552 runs for the given speed are interpolated and a temporary database of 888 rutting data points is generated using a power law equation.
2. Two structures having HMA thicknesses bracketing that of the actual structure are identified and are then used in the interpolation scheme to generate the actual thickness.
3. The structures are subdivided into sublayers. Due to Excel Solver limitations, the sublayering may not be rational.
4. The database is now reduced to *(x sublayers)·(12 environmental sites)·(2 binders types) = (24·x)* rutting data points and the actual structure.
5. The database and the actual structure are now solved (using Excel Solver) to generate $T_{eff}$ and $E_{eff}$ for all sublayers, for the two binders grades and twelve climatic sites.
6. The actual pavement structure with its own material properties is used in two interpolations, first using the relationship *rut depth*-$T_{eff}$ of the twelve sites and second using the relationship *rut depth*- $E_{eff}$ of the two binder grades.
7. The total HMA rut depth is computed by summing all the sublayer contributions.

Because the Excel Solver solution used in this interpolation scheme is time consuming, the material properties of the actual structure are only used with the actual structure. The entire computational process for the database is conducted for the original material properties of the database. Excel Solver must be run for every HMA thickness. However, by changing the sequence above to conduct step 2 between steps 5 and 6, the same accuracy can be achieved and the sublayering limitation can be removed.

*4.1.3 Fitting the Database Rut Contributions of the Sublayers*

Using the revised approach discussed in Section 4.1.2, all 3552 rutting points are fitted only once and the equations are stored for later use in the computations.

This approach represents an enhancement of Sotil's methodology. The following power law model used is:

$$\Delta RD = p_0 (T_{eff})^{p_1} (E_{eff})^{p_2} (v)^{p_3} \quad (4)$$

Where:

v = vehicle speed in mph

$p_0$, $p_1$, $p_2$ and $p_3$ = parameters obtained from fitting the database using Excel Solver.

This process yields 37 different equations or one for each possible sublayer shown in Table 2. Figure 14 illustrates the fitting obtained for the first sublayer in an 8-inch HMA structure. Figure 15 presents the results of fitting all 37 sublayers. In both examples, the fitting is very good, with $R^2$ values greater than 0.98.

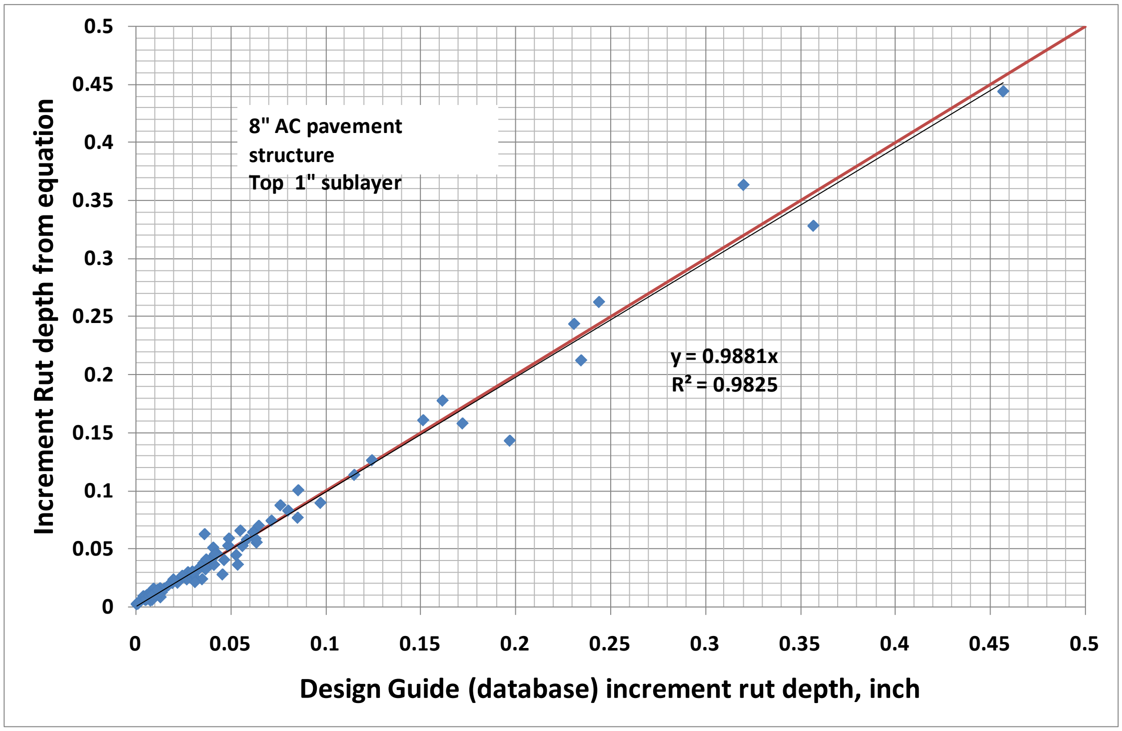


**Figure 14. Illustration of the fitting of the rutting contribution of one sublayer**

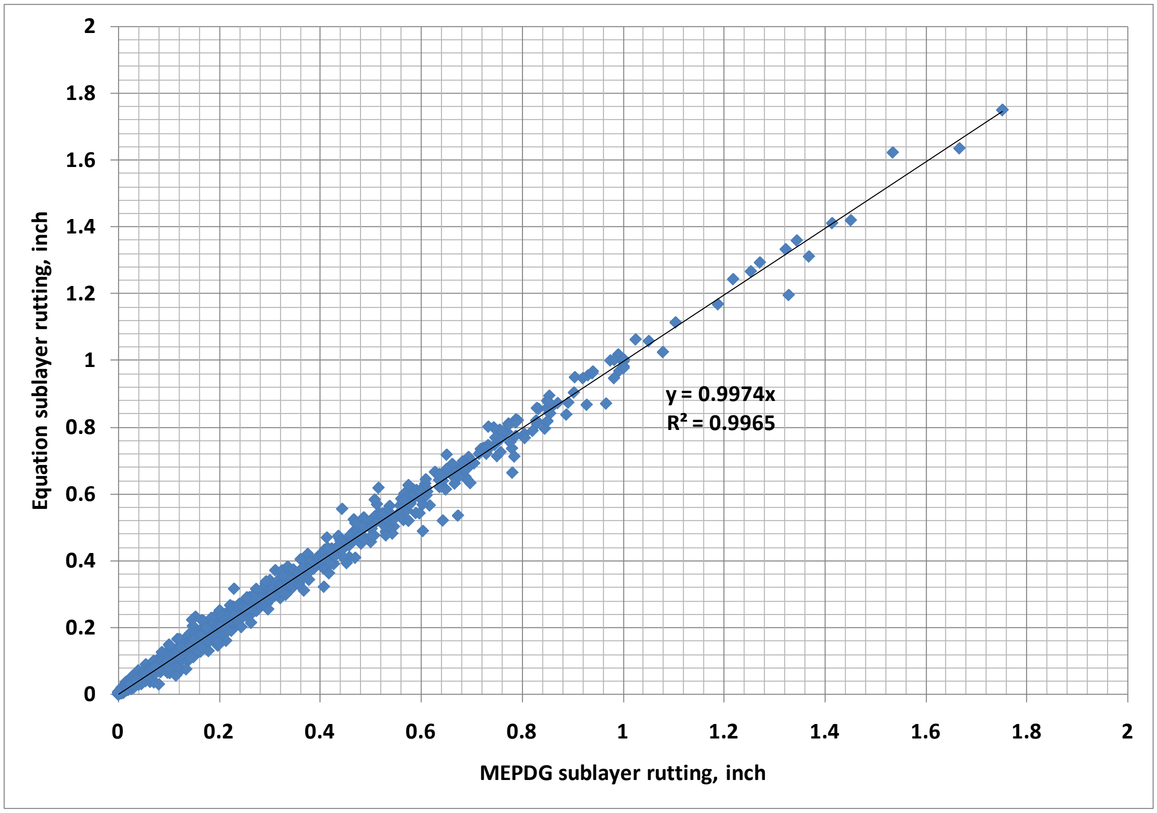



**Figure 15. Illustration of the fitting of the rutting contributions for all 37 sublayers**

*4.1.4 Rut Depth Prediction*

The procedure for predicting the rut depth in the HMA layers includes the steps described in the following sections.

**4.1.4.1 Rut Depth Contribution of a Sublayer** The rut depth contribution of a given sublayer is computed using Equation 4 with the corresponding parameters $p_i$. All sublayers above and including the actual sublayer are transformed to equivalent sublayer thicknesses using Odemark's transformation. At mid-depth of a given sublayer *n*, the effective depth $z_{eff}$ is computed as follows:

$$Z_{eff} = \sum_{i=1}^{n-1}\left( h_i \sqrt[3]{\frac{E_i}{E_{SG}}} \right) + \frac{h_n}{2}\sqrt[3]{\frac{E_n}{E_{SG}}} \qquad (5)$$

Where:

$h_i$ = thickness of sublayer *i* (*i*=*n* for the actual sublayer)

$E_i$ = modulus of sublayer *i*, in psi

$E_{SG}$ = subgrade modulus, in psi (assumed to be 15,000 psi)

The effective length $L_{eff}$ of the load pulse and the loading frequency of the sublayer are then obtained with the following equations:

$$L_{eff} = 2 \cdot (Z_{eff} + a)$$
$$Freq = 17.6 \cdot v / L_{eff} \qquad (6)$$

Where a = radius of contact area, in inches (see Figure 16).

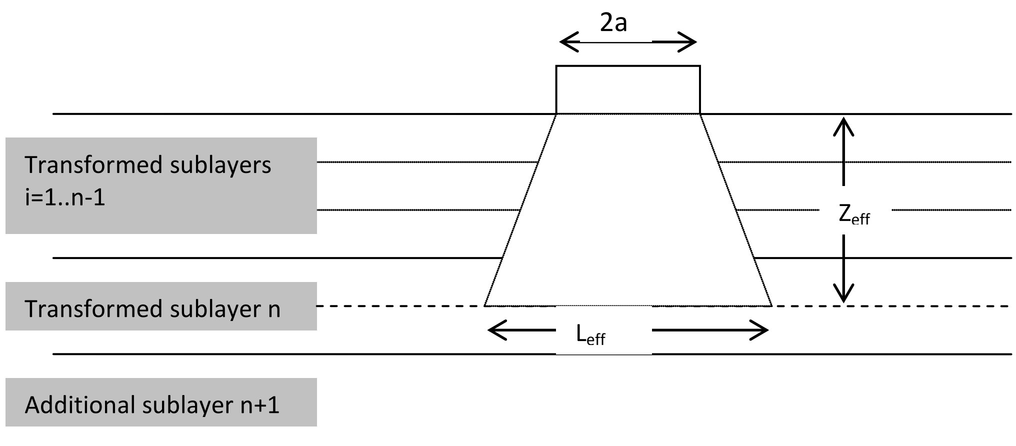



**Figure 16. Structure used to calculate the effective depth and loading length**

The effective temperature can now be calculated. The effective temperature is dependent on the sublayer modulus used to compute the equivalent thickness. The final step is to compute the sublayer modulus using Equation 3 together with the gradation, binder properties, and the variables $T_{eff}$ and Freq. Because of the interdependence of the $E_{eff}$ and $T_{eff}$, an iterative process is required. The rut depth contribution of the sublayer is computed using Equation 4 with the given vehicle speed and the variables $T_{eff}$ and $E_{eff}$ are determined.

**4.1.4.2 Rut Depth Computation for a One-Layer Structure** The total rut depth is computed as the sum of the rutting contributions of all sublayers in the structure. However since the HMA thickness may not correspond to one of the structures in the database, an interpolation scheme is needed. This interpolation is illustrated in Figure 17 for the example of a 7-inch HMA structure. The structures in the database that bracket this thickness are the 6 and 8 inch structures, which are designated as structures I and II in Figure 17.

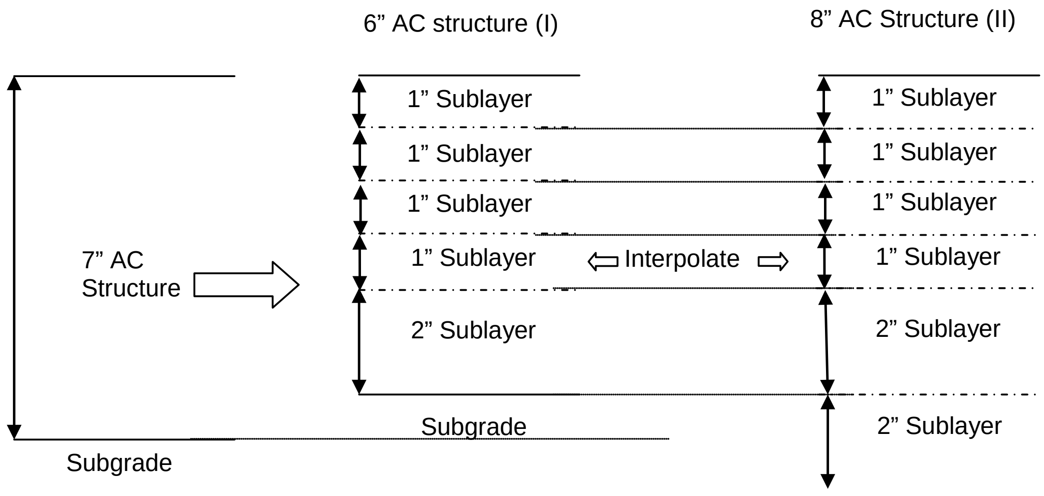



**Figure 17. Structures for the interpolation scheme.**

The rut depth contributions of each sublayer in structures I ($\Delta RD^{I}_{i}$) and II ($\Delta RD^{II}_{i}$) are computed and interpolated as follows:

- The rut depth contribution $\Delta RD_i$ of the sublayers i=1 to 5 is computed using:

$$\Delta RD_i = \Delta RD_i^I + (\Delta RD_i^{II} - \Delta RD_i^I) \cdot \frac{hac - hac^I}{hac^{II} - hac^I} \tag{7}$$

- For the last sublayer in structure II, the rut depth contribution to the actual structure is:

$$\Delta RD_i = 0 + (\Delta RD_i^{II} - 0) \cdot \frac{hac - hac^I}{hac^{II} - hac^I} \tag{8}$$

- The total rut depth, RD, in the 7-inch HMA structure is then computed as the sum:

$$RD = \sum_{i=1}^{n} \Delta RD_i \tag{9}$$

Where:

hac, $hac^{I}$ and $hac^{II}$ = HMA thicknesses of the actual structure, structure I, and structure II, respectively

i =index of the sublayer number

**4.1.4.3 Rut Depth Computation For Two- And Three-Layer Structures** When a structure contains more than one HMA layer, the total rut depth is computed as the sum of the rut depths computed for each layer. The interpolation is illustrated by the example of a 7-inch HMA structure composed of two different HMA mixtures (see Figure 18). The top layer (layer A) is 2.4 inches thick ($hac^A$=2.4) and the second (layer B) is 4.6 inches thick ($hac^B$=4.6).

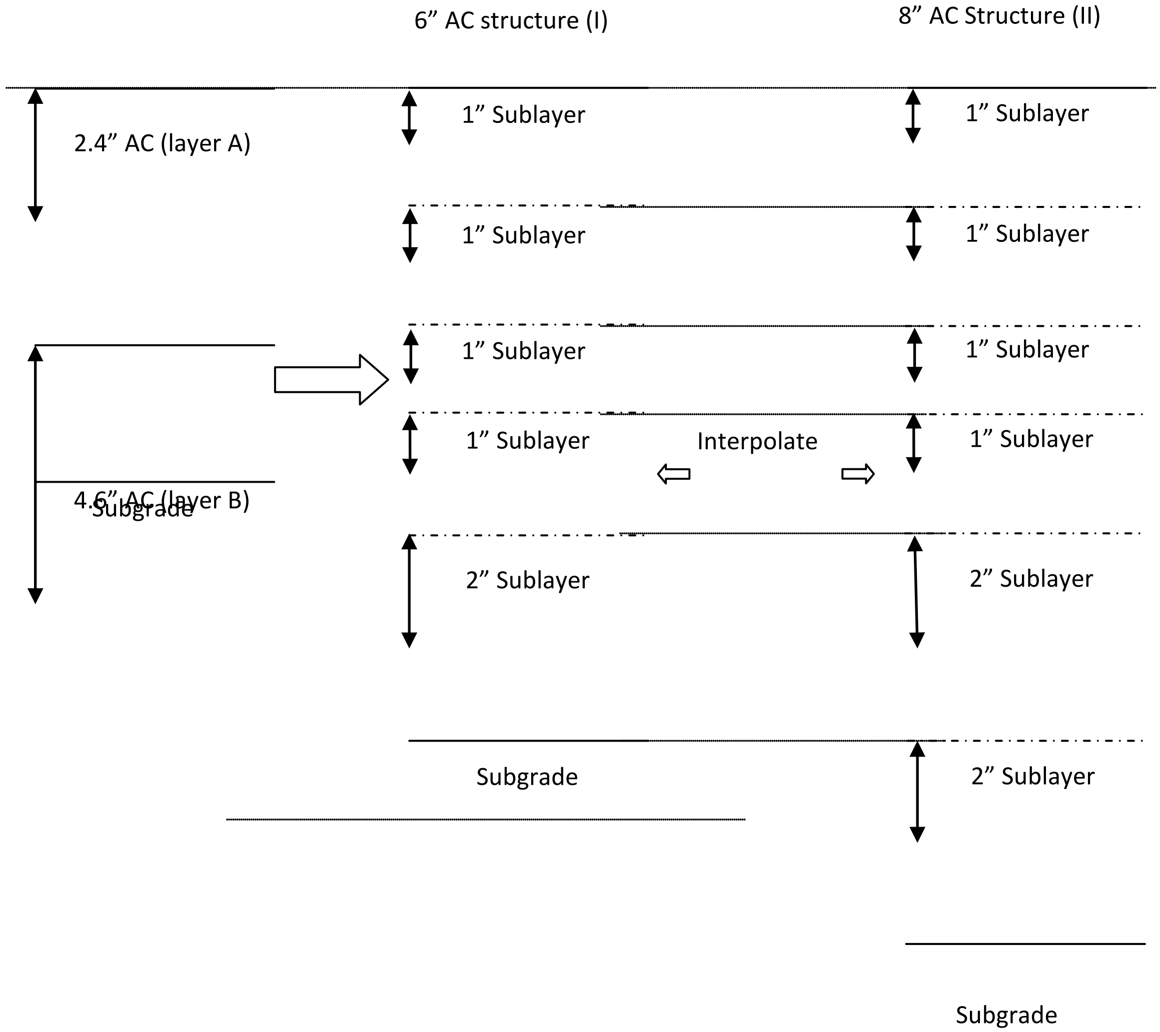



**Figure 18. Structures for the interpolation scheme in a two layer structure.**

For layer A, the rut depth contributions for bracketing structures I ($\Delta RD^{I}_{i}$) and II ($\Delta RD^{II}_{i}$) are computed for the first three top sublayers (i=1, 2 and 3) using the material properties of layer A (gradation, performance grade, etc.). The rut depth contributions of these three sublayers are computed using equation 7. As the thickness of layer A does not correspond to the database sublayering, an additional interpolation is needed. The rutting in layer A ($RD^{AA}$, rut depth in layer A with material properties of layer A) is computed as follows:

$$RD^{AA} = \sum_{i=1}^{2} \Delta RD_i + \Delta RD_3 \cdot \frac{hac^A - (hac_1 + hac_2)}{hac_1 + hac_2 + hac_3} \qquad (10)$$

Where:
$hac_i$ = thickness of sublayer *i* (in this case $hac_1$= $hac_2$ = $hac_3$ =1 inch)

For layer B, the computations are made in two steps, using the material properties of layer B (gradation, performance grade, etc.) for the whole structure (both layers A and B).

a) The rutting in layer A ($RD^{AB}$, rut depth in layer A with material properties of layer B) is computed using equation 9.
b) The rutting in the 7-inch structure composed of layer B material ($RD^{B}$) is computed using equations 7, 8, and 9 for uniform structure.
c) The rut depth in layer B is computed as $RD^{BB} = RD^{B} – RD^{AB}$.

The rut depth of the entire structure is finally computed as the sum RD= $RD^{AA}$ + $RD^{BB}$.

## 4.2 Fatigue Cracking Model

The fatigue cracking model is based on 8970 runs of the MEPDG Version 0.7-0.8 (6), including 7776 runs for model development and 1194 for verification. The runs for model development included:

- Three different climatic sites: Grand Forks ND, Oklahoma OK, and Key West FL.
- Design lives of 5 and 15 years with the same traffic load of one million E18KSAL.
- Six different HMA layer thicknesses: 1, 2, 4, 6, 8, and 20 inch over the subgrade (i.e., a two-layer system).
- Four different vehicle speeds: 0.5, 15, 45, and 60 mph.
- One aggregate gradation for the HMA layer (retained on ¾-inch sieve =0%, retained on 3/8-inch sieve = 26.8%, retained on No. 4 sieve = 46.41%, and passing No. 200 sieve = 8.28%) and one VMA value (VMA=20) with three combinations of air voids ($V_a$) and binder content ($Vb_{eff}$).
- Three binder grades: PG 82-10, PG 64-22, and PG 52-40.
- Five $E_{Foundation}$ (Composite Foundation Modulus or subgrade modulus for a two layer system): 3, 8, 25, 75, and 250 ksi.

### *4.2.1 Parameter Definitions*

The effective temperature uses the same climatic variables as in equation 2 for permanent deformation. The depth variable is not explicitly included. The effective temperature for fatigue cracking is thus defined as:

$$T_{eff} = -1.016814\sqrt{Freq_{eff}} - 17.691387 + T_f$$
$$T_f = 1.11(MAAT) + 1.254(\sigma_{MAAT}) - 1.132(Wind) + 0.337(Sunshine) + 0.071(Rain) \quad (11)$$

Where:
$T_{eff}$ = Effective Temperature for fatigue cracking, °F
$Freq_{eff}$ = Effective loading frequency computed at the bottom of the HMA layers, without transformation, Hz
MAAT = mean annual air temperature, °F
$\sigma_{MAAT}$ = standard deviation of the mean monthly air temperature
Wind = mean annual wind speed, mph
Sunshine = mean annual sunshine percentage, %
Rain = cumulative annual rainfall depth, inches

The effective modulus of the HMA material for fatigue cracking is computed using the Witczak Predictive Equation (Equation 3).

*4.2.2 Development of the Fatigue Model for a Two-Layer System*

The fatigue (alligator, bottom-up) cracking results obtained from the 7776 MEPDG runs were analyzed to develop a comprehensive model for predicting the structure-allowable fatigue resistance as a function of the effective HMA modulus, HMA thickness, HMA mixture volumetric parameters, and composite foundation modulus. The equation used to compute the allowable number of repetitions to fatigue failure. $N_f$, is:

$$\begin{aligned}\log N_f = 6 - &\left\{\begin{matrix}\left[b_1(\log(hac))^2 + b_2\log(hac)\right]\cdot\log(E^*_{eff}) \\ + b_3(\log(hac))^2 + b_4\log(hac) + b_5\end{matrix}\right\} * \left(\log(E_{cf})\right)^2 \\ &+ \left[b_6\left(\log(E^*_{eff})\right)^2 + b_7\log(E^*_{eff}) + b_8\right] * \log(E_{cf}) \\ &+ \left[b_9(\log(hac))^2 + b_{10}\log(hac)\right] * \left(\log(VFB)\right)^2 \\ &+ \left[b_{11}(\log(hac))^2 + b_{12}\log(hac) + b_{13}\right] * \log(VFB) \\ &+ b_{14}\left(\log(E^*_{eff})\right)^2 + \left[b_{15}(hac)^2 + b_{16}(hac) + b_{17}\right] * \log(E^*_{eff}) + b_{18} \quad (12)\end{aligned}$$

Where:
hac = HMA thickness, in
$E^*_{eff}$ = effective HMA modulus, psi
$E_{cf}$ = composite foundation modulus, ksi,
VFB = voids filled with bitumen, and
b1 to b18 = regression constants

The fatigue cracking at *n*, the number of traffic repetitions of interest, can then be determined by the ratio $n/N_f$. This same model form was found to be valid for both thin and thick HMA layers. The effective HMA modulus, which was incorporated in the damage prediction model, is in turn a function of the environmental characteristics (effective temperature), traffic speed (loading frequency), voids filled with bitumen, HMA mixture gradation, and binder viscosity. In the case of multiple HMA layers, the upper layers are transformed into an equivalent layer having the modulus of the bottom layer using Odemark's transformation.

### *4.2.3 Development of the Fatigue Model for a Three-Layer System*

A methodology for transforming a three-layer system (HMA layer on top of a base-subbase layer over the subgrade) into a two-layer system (HMA layer on top of a composite foundation) was also developed. This lookup procedure is based on the concept of equal tensile strain at the bottom of the HMA layers, i.e., the two-layer system with a composite foundation modulus will have the same tensile strain as the original multilayer system. The database and algorithm for layer transformation are provided in a separate spreadsheet.

In the case of two granular layers, base and subbase, the subbase layer is transformed into an equivalent layer having the modulus of the base layer using Odemark's transformation. Then the three-layer system is transformed into a two layer system using the methodology described above.

A comprehensive analysis of the suggested alligator fatigue cracking methodology was conducted with the purpose of verifying its accuracy and practicality. A total of 1194 simulations were executed using the MEPDG and the spreadsheet methodology described here. Comparison of the outputs (Figure 19) indicates that the methodology provides reasonable predictions of alligator fatigue cracking.

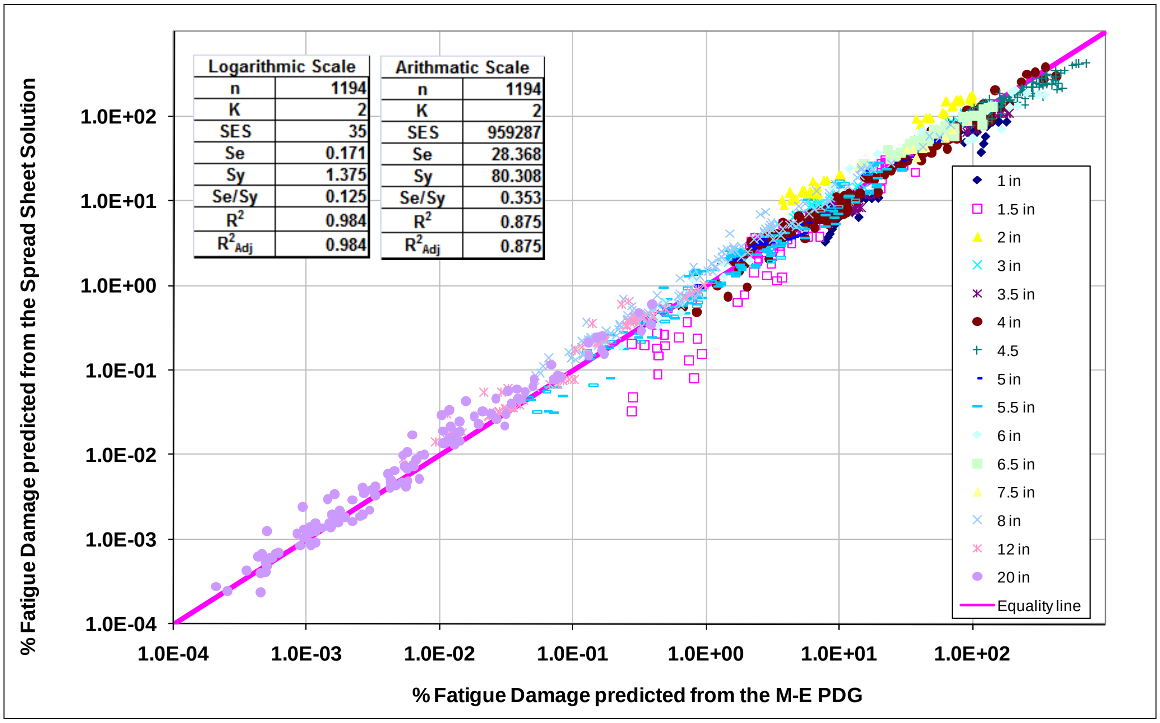



**Figure 19. Comparison of Fatigue Damage between MEPDG and Developed Model (6)**

### *4.2.3 Fatigue Cracking Prediction*

The program predicts the fatigue cracking in an HMA layer through the following steps:

- Read the environmental conditions, layer thicknesses, material properties, and traffic
- Compute $T_f$ representative of the site
- Compute lower HMA layer modulus and transform middle and upper HMA layers into an equivalent HMA layer
- Compute composite foundation modulus using spreadsheet interpolation
- Compute $N_f$ using equation 12
- Compute damage $D = n/N_f$
- Compute fatigue cracking using the equation in the MEPDG:

$$FC = \left( \frac{100}{1 + \exp\left( C_1 * C_1' + C_2 * C_2' * \log_{10}(D) \right)} \right) \quad (13)$$

where:
$C_1 = 1.0$
$C_2 = 1.0$
$C'_1 = -2 * C'_2$

$C'_2 = -2.40874 - 39.748*(1+ hac)^{-2.856}$
$FC$ = Fatigue cracking (as a % of lane area)
$D = 100*n/N_f$ = Damage in percentage

## 4.3 Thermal Cracking Model

The program's thermal cracking model is substantially different from its permanent deformation and fatigue cracking models. A preliminary sensitivity study conducted with thermal fracture results obtained with the MEPDG revealed the difficulty of developing accurate, closed-form solutions using probabilistic approaches, including linear and non-linear regression methods. As a consequence, a mechanistic-based approach was developed that is derived from the same fundamental theory underlying the current MEPDG thermal fracture subroutine. A FORTRAN code similar to the "master.exe" and "tcmodel.exe" codes in the MEPDG (7) was developed that uses the identical pavement climatic files needed to compute thermal cracking in the MEPDG. These files are generated using climatic "hcd" files and "im.exe" code. For this reason, the thermal cracking model in this program takes a longer time (a few minutes rather than seconds) to run than the other models. However, the results closely compare to those obtained with the MEPDG.

In the thermal cracking model, the mixture air voids and binder contents are used to generate creep compliance curves (as in a MEPDG Level 3 analysis). The curve-generating process produces "random" variations of the parameters used to compute the thermal cracking. Figure 20, for example, shows the variation of the m–parameter of the master creep compliance curve as function of the air voids (where the effective binder volume is 9.5%). The m-parameter decreases with increasing air voids, but the decrease is not smooth. The same effect is noticed in the predicted amount of thermal cracking (the blue points and line in Figure 20). In view of these results, the thermal cracking results are subjected to a second-order polynomial smoothing procedure before the contours are drawn. Figure 21a sand 21b present a 3D chart of the thermal cracking surface before and after smoothing of the raw results, respectively. Figure 22a and b present contours of thermal cracking before and after smoothing. The final graphical solution displays smooth contour lines.

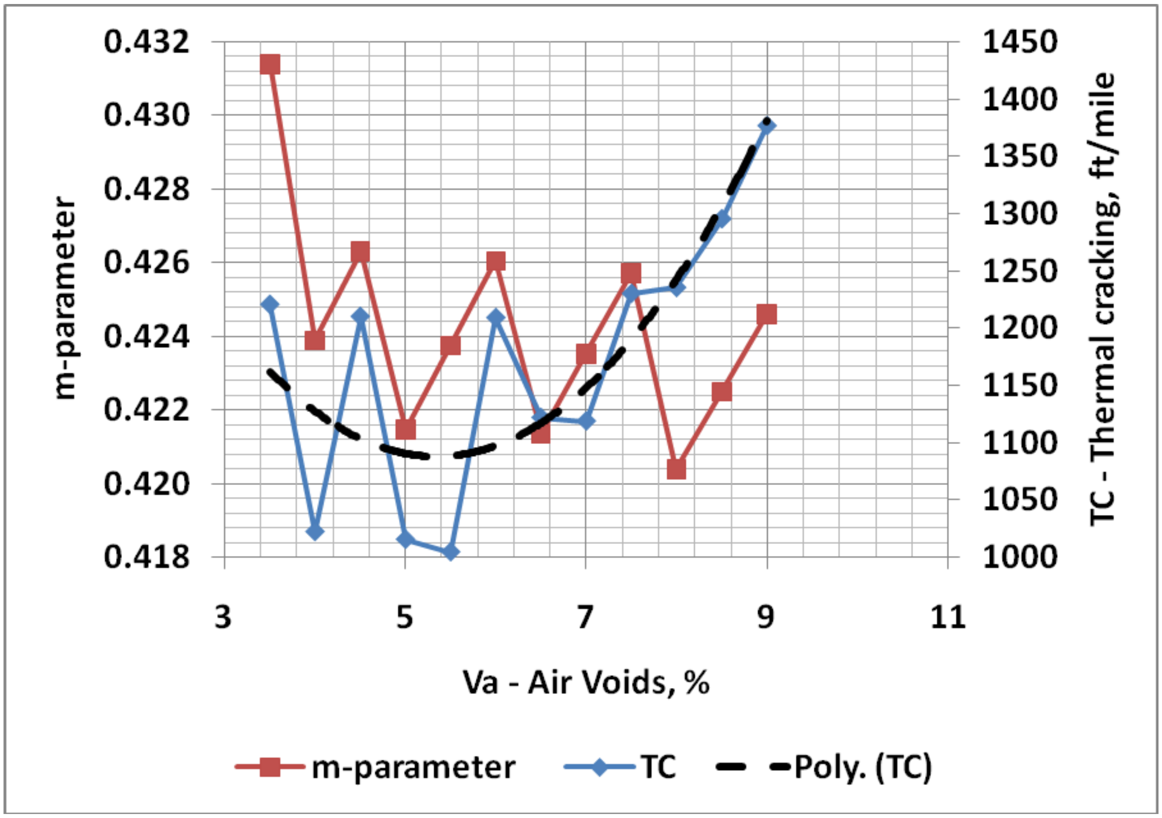
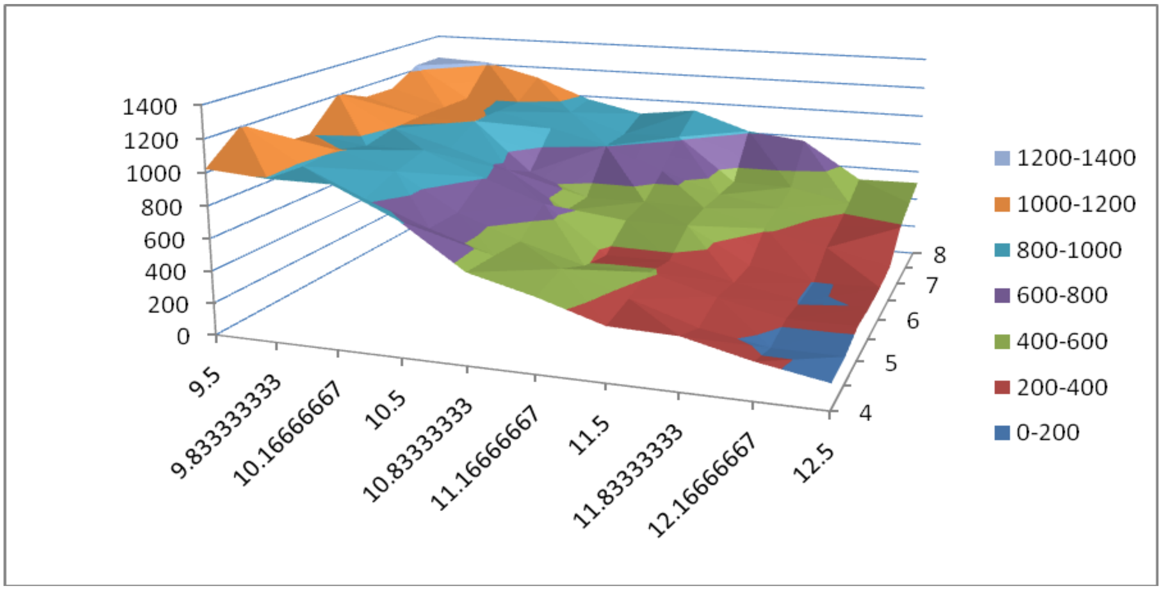
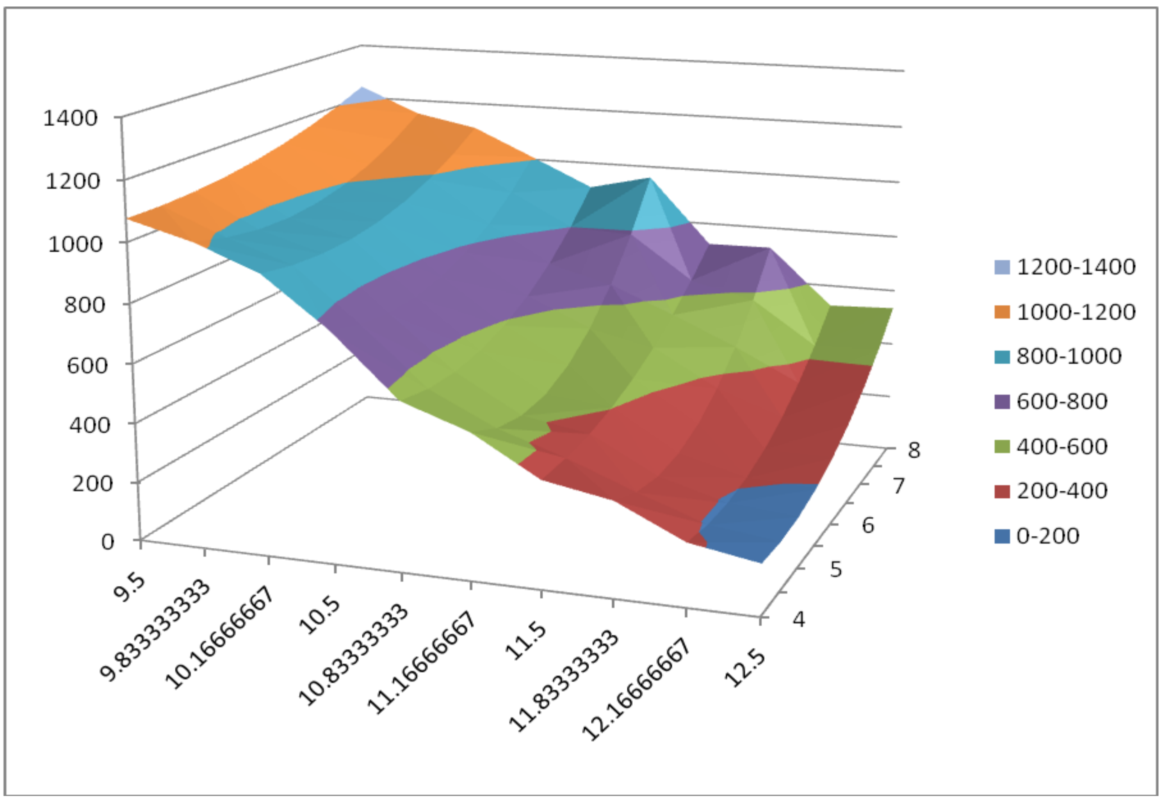



**Figure 20. Variation of m and thermal cracking with percent air void**

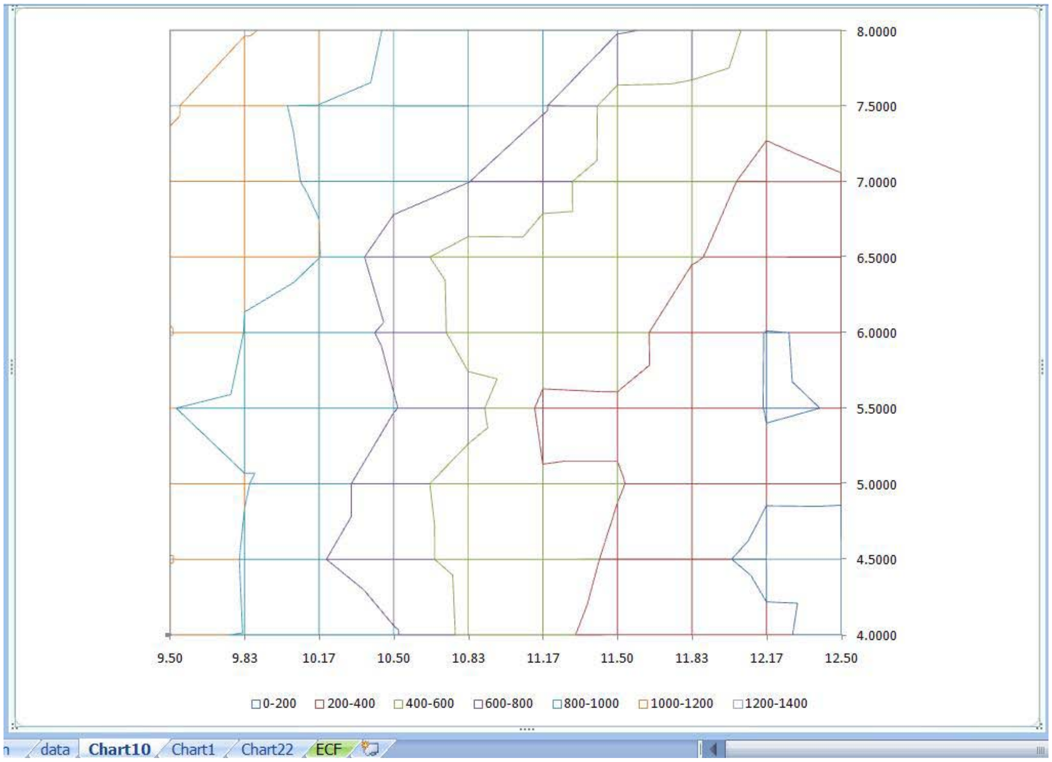



(a)

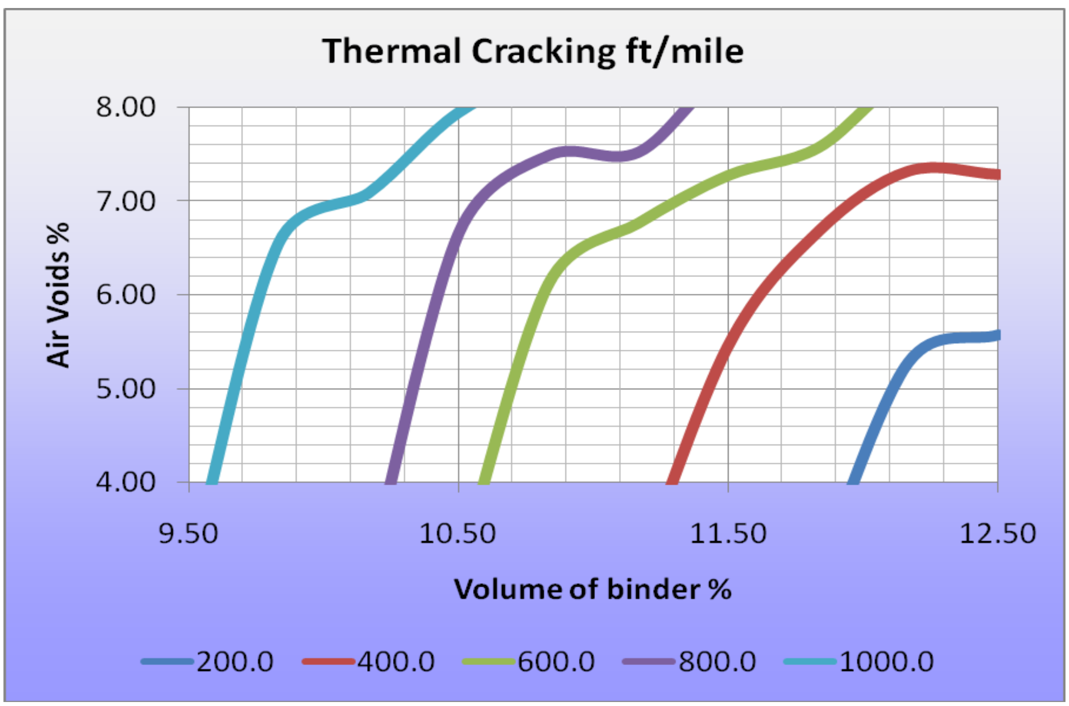



(b)

**Figure 21. 3D plots (a) before and (b) after smoothing**




(a)




(b)

**Figure 22. Contour plots (a) before and (b) after smoothing**

# 5 USER GUIDE AND EXAMPLES

This section presents two example analyses of HMA mixture performance made with the program. It is important to note that while a performance analysis must be conducted on the "final" structure, which includes all layers, the results of the analysis will display the sensitivity of predicted performance to the variables (air voids and effective binder volume) only for the layer for which the mixture is being designed.

Further, it is important to note that:

1. The majority of HMA rutting usually develops in the upper 4 to 6 inches of the pavement. The effect of any HMA layer located below this depth is generally attributed to the thickness effect and not to the layer's volumetric properties.
2. The fatigue cracking analysis only uses the properties of the lowest HMA layer. Intermediate and upper HMA layers, if present, are transformed into equivalent layers. Therefore, their properties will affect only the pavement's equivalent HMA thickness that, in turn, impacts the performance through the thickness effect. Differences in crack propagation due to differences in mixture properties in the several HMA layers are not accounted for by either the MEPDG or this program.
3. The thermal cracking analysis uses only the top HMA layer properties and the total HMA thickness. The properties of the intermediate and lower HMA layers are not accounted for by either the MEPDG or this program.

## *5.1 User Guide*

The cells in the "User Input" sheets are colored as follows: (a) yellow for input, (b) red for computed values (no entries), and (c) blue for control buttons. Data should be typically entered in the following order:

1. Enter general information. The expected time of construction is a necessary input variable for a thermal cracking analysis.
2. Enter traffic data. In this program (unlike the MEPDG), traffic is only handled through equivalent 18 kip single axle wheel loads (E18KSAL).
3. Enter climatic information either by using the control button and selecting a weather station(s) from the dropdown list or by manually entering the required data.
4. Enter the layer number to be analyzed in cell E25.
5. Enter the material properties for all layers (using the blue button). Properties must be entered for all layers, not just the layer being analyzed.
6. Click the layer to display forms for entering the layer materials data.
    i. Input binder, aggregate, and mixture volumetric data.
    ii. Select the mix design specification, or input your own specification.

iii. Review the mix design window of acceptable $V_a$ and $V_{beff}$ values. The user-defined target binder content will also be displayed to verify that it is contained within the specification limits.
iv. If the specification is not met, the target binder content may be adjusted until it falls within the window of acceptable values.
v. Input the aggregate gradation. The highlighted sieve sizes are the minimum required.
vi. Input the in-situ air voids and its tolerance.
vii. Repeat this process for all HMA layers.

7. Enter layer thicknesses.
8. Enter the base/subbase and subgrade properties. This information is primarily required for the fatigue cracking analysis.
9. Enter the distress criteria for each distress of interest.
10. Run the performance analysis by clicking the blue buttons for each distress of interest. Output charts will be generated for each distress showing contour lines of predicted distress on a plot of the in-situ volumetric properties. The specification criteria and the target value will be shown on the plot for comparison.

If the analysis shows that the predicted distresses for the specified mixture fail to meet the distress criteria, then either the mix design or the pavement structure may be modified by returning to the proper input cells.

The following sections present two examples of using the program. The first example is based on a North Dakota ½-inch Class 29 specification, which is a Superpave-type specification. The second example uses the Asphalt Institute ½-inch heavy traffic specification, which is a Marshall-type specification. These two specifications were selected in order to illustrate the use of the mix design window with widely differing specifications. The reader is encouraged to practice the use of the program by entering the data and confirming the outputs shown for the examples.

### *5.2 Example 1: Superpave Mix Design Procedure*

The first example is based on a mix design intended for use in North Dakota. The data used in this example are as follows:

1. Project information:
    a. Project ID = 1
    b. Project Name = Example
    c. City = Bismarck
    d. County =
    e. State = North Dakota
    f. Date of analysis = 10/20/2010
    g. Expected construction date = 7/5/2008 (required for thermal cracking analyses).
2. Traffic data:

a. Vehicle speed = 60 mph
b. Design life = 20 years
c. Initial daily E18KSAL = 500
d. Traffic growth rate = 1%
e. Total E18KSAL over the design life = 4,038,527

3. Climate data:
   a. Location = Bismarck Municipal Airport
   b. Mean annual air temperature = 43.68°F
   c. Mean monthly air temperature standard deviation = 20.62°F
   d. Mean annual wind speed = 8.06 mph
   e. Mean annual sunshine = 62.94%
   f. Annual cumulative rainfall depth = 17.87 inches
4. Structure data[1]:
   a. HMA surface layer thickness = 6 inches
   b. Granular base thickness = 6 inches
   c. Granular base modulus = 30,000 psi
   d. Granular subbase thicknesses = 8 inches
   e. Granular subbase modulus = 24,000 psi
   f. Subgrade modulus = 5,000 psi
5. Distress Criteria:
   a. HMA (only) Rut Depth = 0.2 inches
   b. Fatigue Cracking = 20%
   c. Thermal Cracking = 1,000 ft/mile
6. HMA Surface Layer Material Properties:
   a. Binder grade: PG 52-34
   b. Binder content: 5.0% (by total weight of mix)
   c. $G_{sb}$ = 2.701
   d. $G_{se}$ = 2.741
   e. $G_b$ = 1.025
   f. Specified air voids for HMA mix design selection: 4%
   g. Specification: North Dakota ½-inch Class 29
   h. Aggregate gradation (% passing):
      i. ¾ inch = 100%
      ii. ⅜ inch = 78%
      iii. #4 = 40%
      iv. #200= 4.1%
   i. Target in-situ air voids: 7%
   j. In-situ air voids limits: ±4%
   k. Calculated in-situ effective binder volume ($V_{beff}$) = 10.2 %
   l. Construction tolerance: ±0.3% (by weight of mix)

[1] The base, subbase and subgrade information are required for the fatigue cracking analyses.

Figure 23 shows the user input screen with all inputs for this example. The user input tab includes general project, traffic, climate, structural, and distress criteria information.

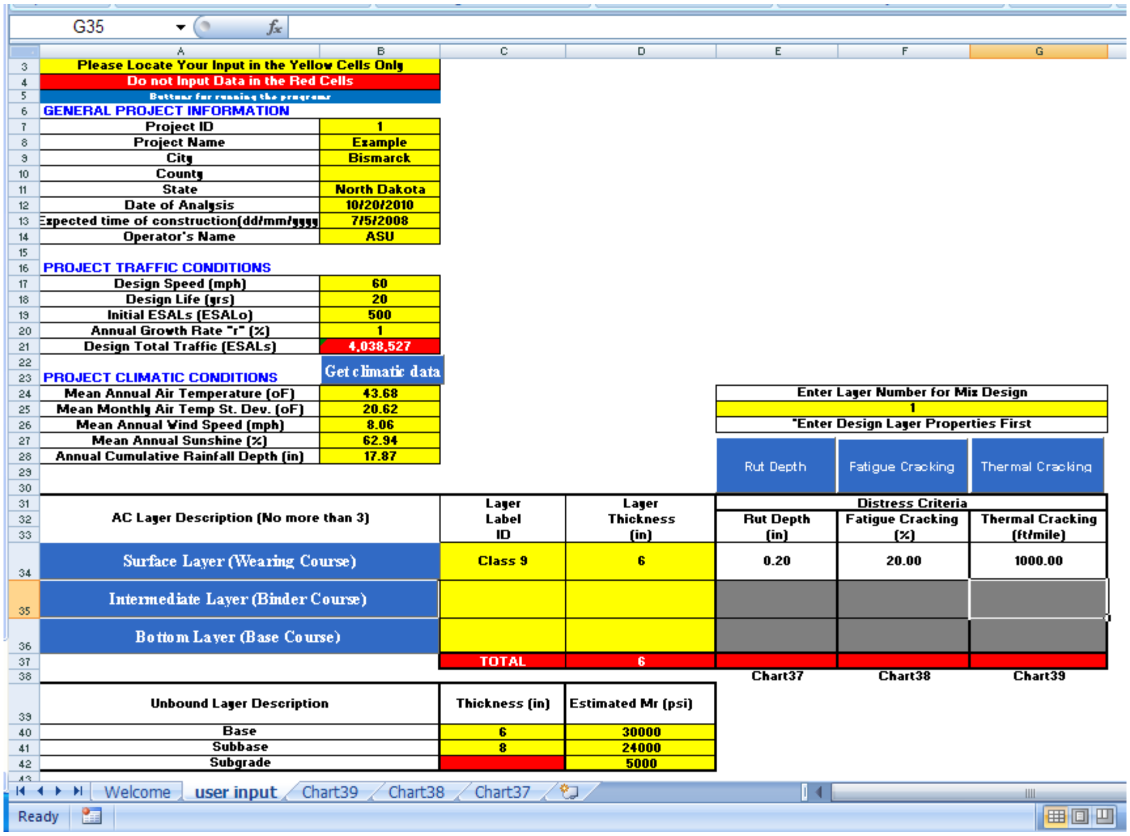



**Figure 23. Example 1 User Input screen**

Figure 24 shows the input screen for the environment/climatic data where the weather station is selected in a process similar to that used in the MEPDG software. In this example, the weather station for Bismarck, ND is selected.

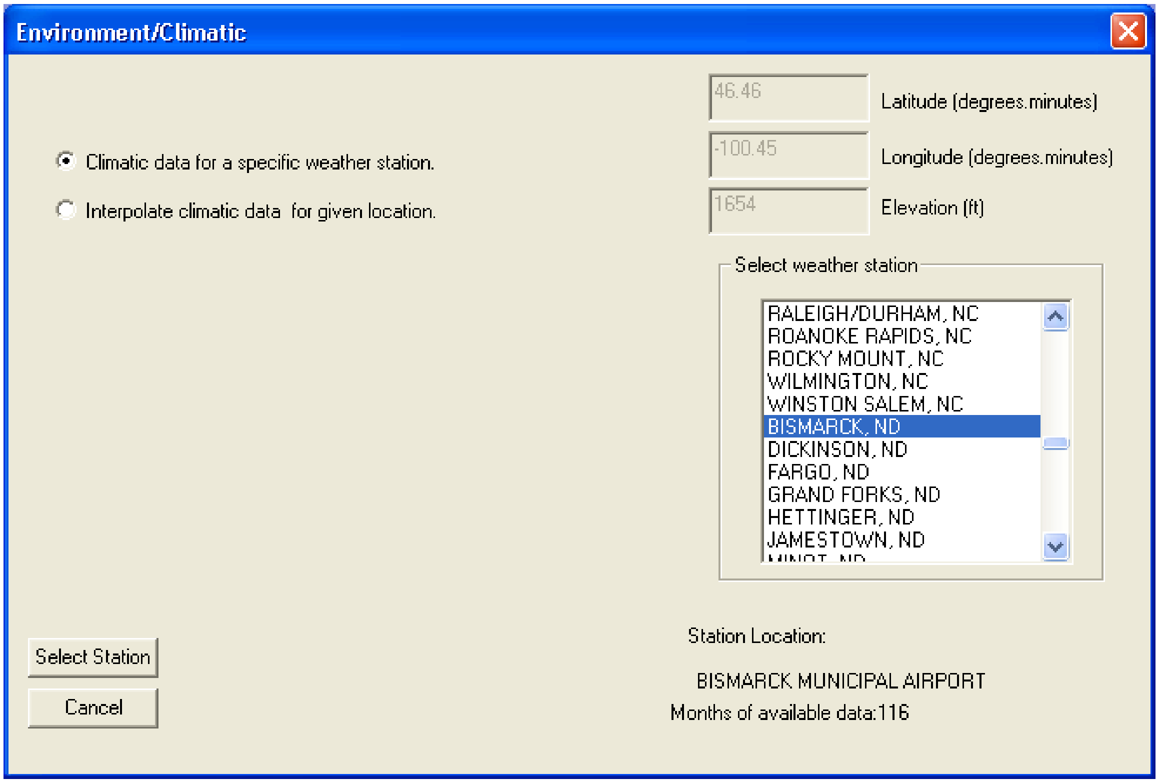



**Figure 24. Example 1 Climate selection screen**

Next, clicking the blue Surface Layer button opens the material properties form (Figure 25) for entry of the mixture material properties (binder type and volumetric properties) in the appropriate cells.

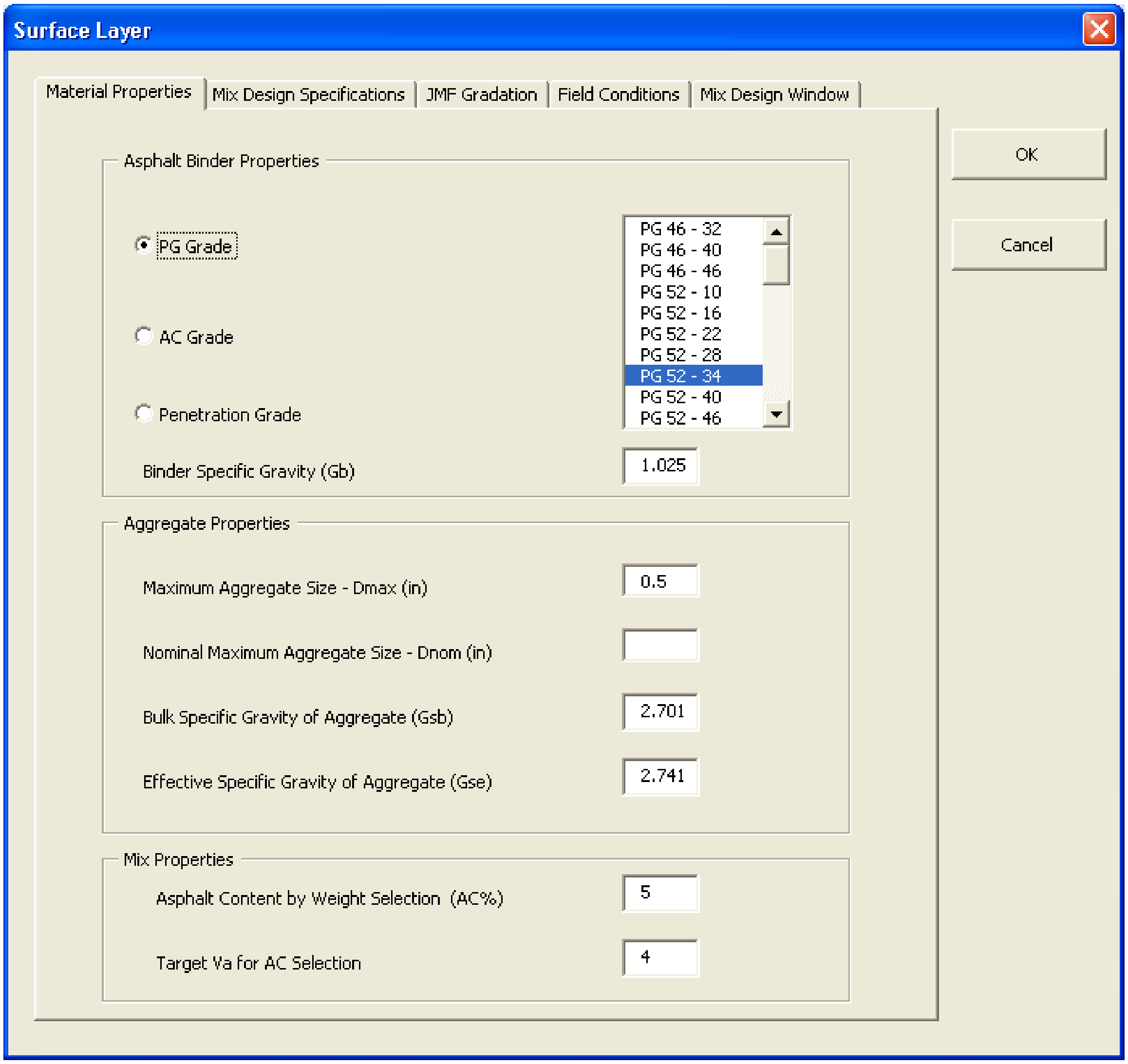



**Figure 25. Example 1 Surface Layer JMF Material Properties screen**

Figure 26 shows the Mix Design Specifications tab with the North Dakota specification selected. As seen in the figure, since the specification follows the Superpave guidelines, the minimum and maximum air voids are set at 4%, which is the Superpave recommended air void value for selection of the mixture asphalt content. In Figure 27 the Mix Design Window tab is selected. As can be seen, since the upper and lower air voids limits are set at 4%, the window collapses into a single line at 4% air voids.

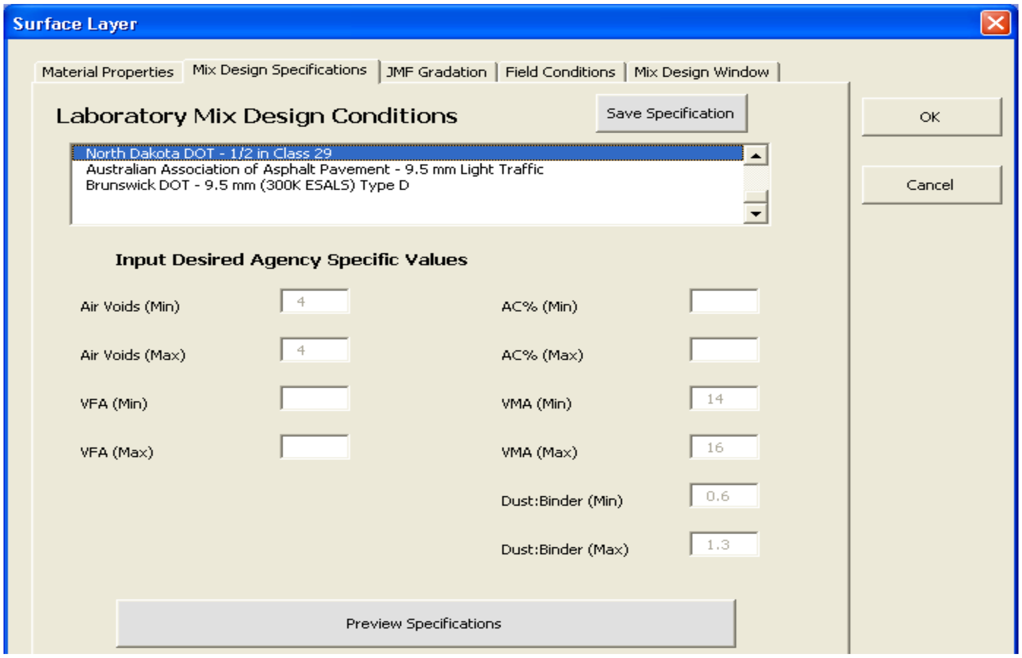



**Figure 26. Example 1 Mix Design Specification screen**

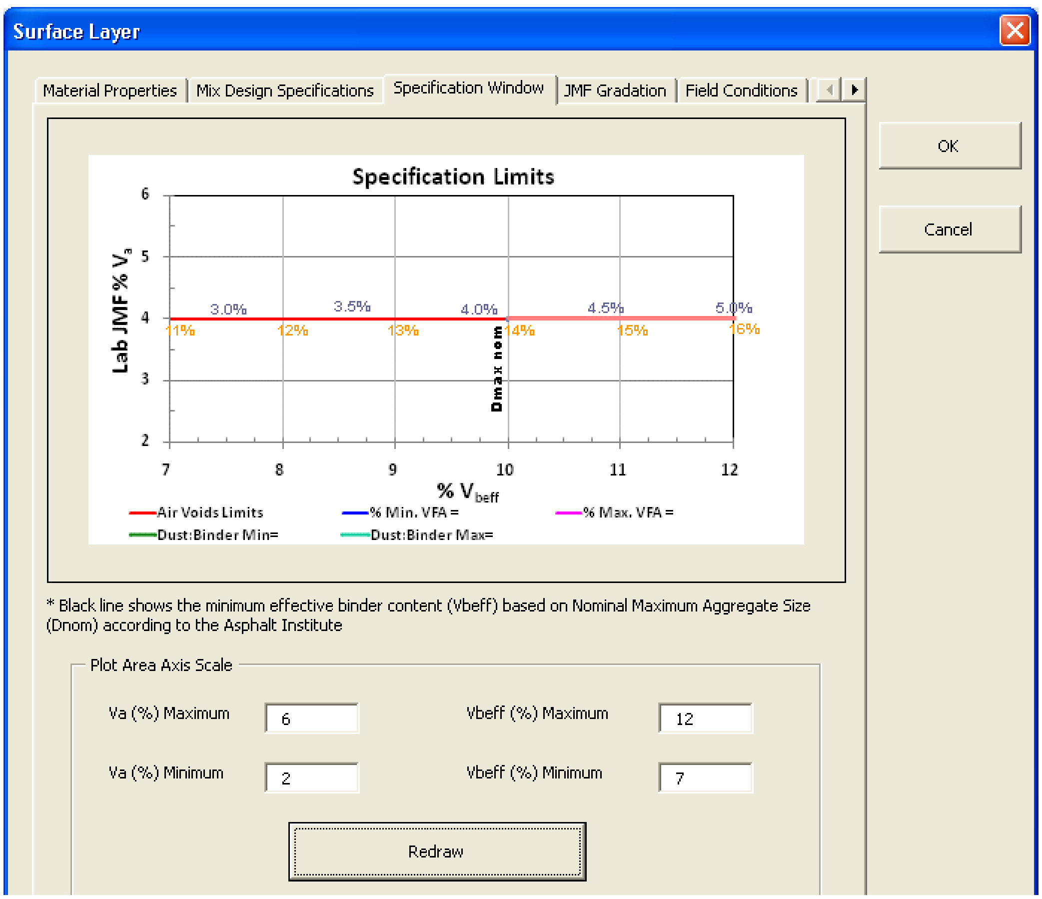



**Figure 27. Example 1 Mix Design Verification screen**

Figure 28 shows the input screen for the JMF Gradation tab; Figure 29 shows the input screen for the Field Conditions tab where in-situ properties are entered. In Figure 29, Air Voids Limits (%) was selected as the field specification. Entering the in-situ air voids and air voids limits in the form sets the minimum and maximum $V_a$ limits. Also, the effective binder volume (based on the in-situ $V_a$) is calculated by Equation 1 as explained below. The construction tolerance sets the allowed limits on the variation of the binder content in the field.

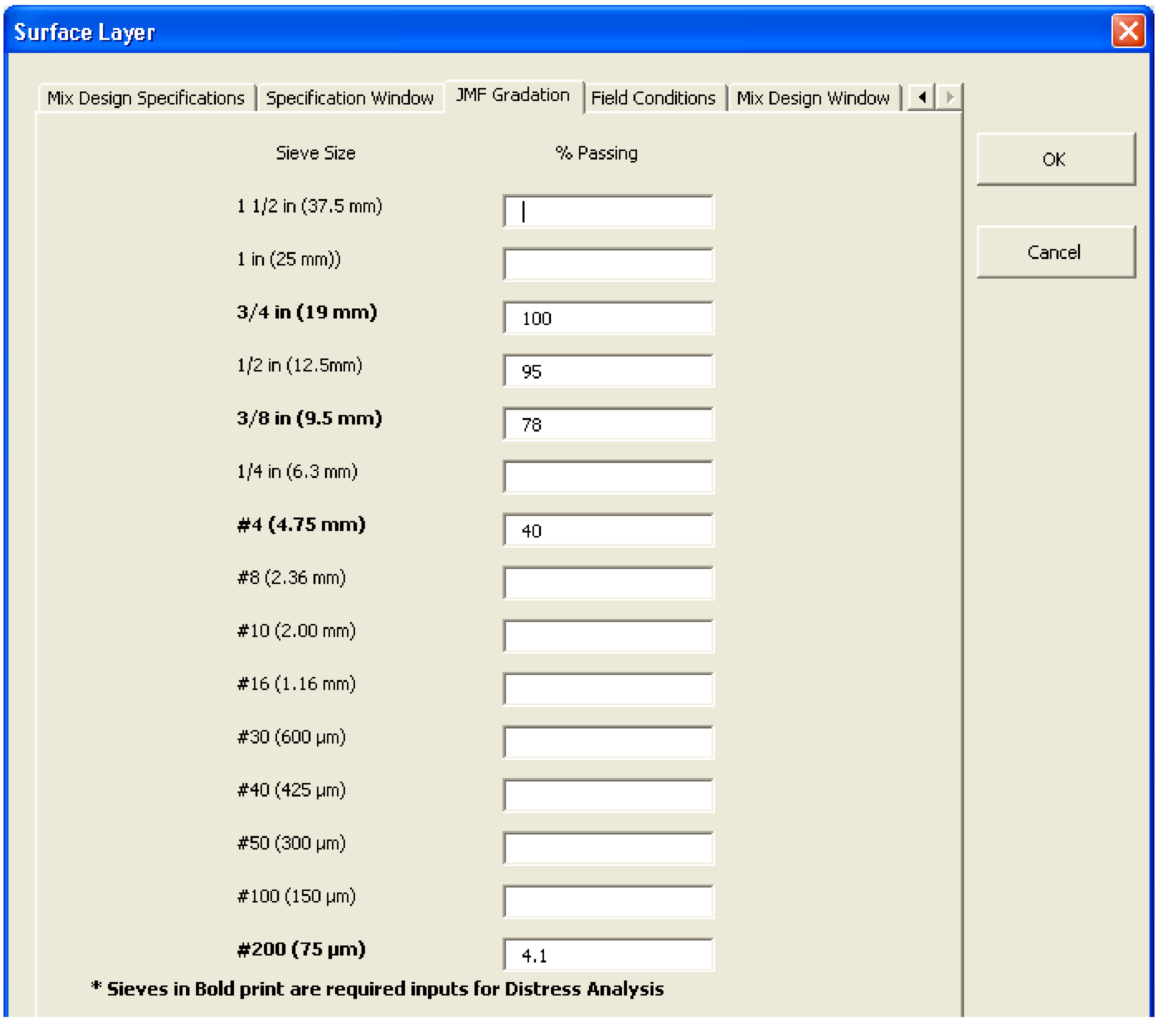



**Figure 28. Example 1 Mix Aggregate Gradation Input screen**

Figure 30 again shows the Mix Design Window screen with the target and specification range set on it.

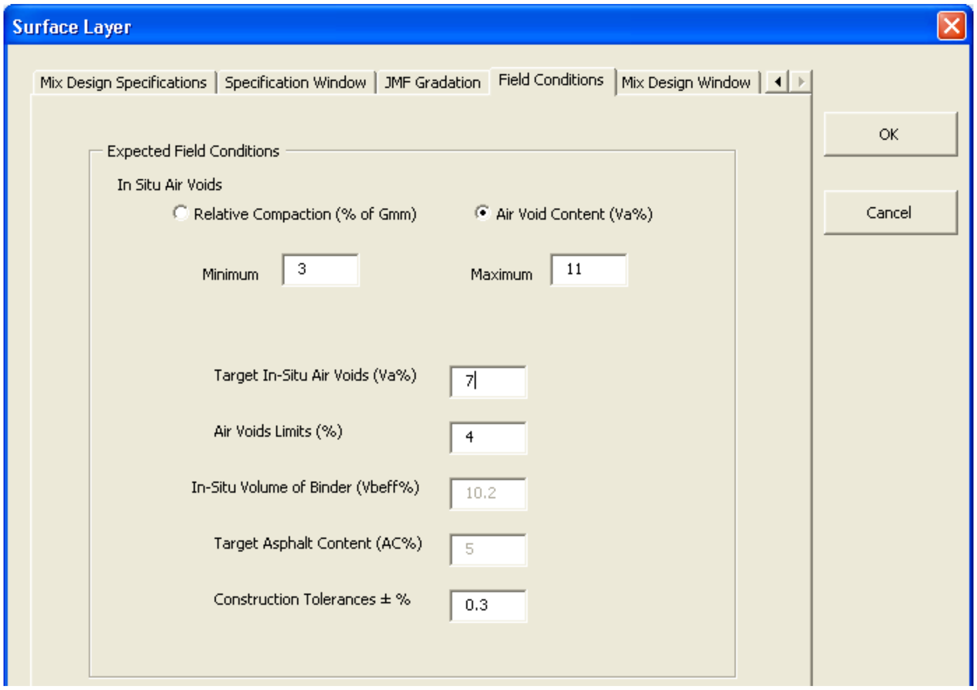



**Figure 29. Example 1 In-Situ Properties Input screen**

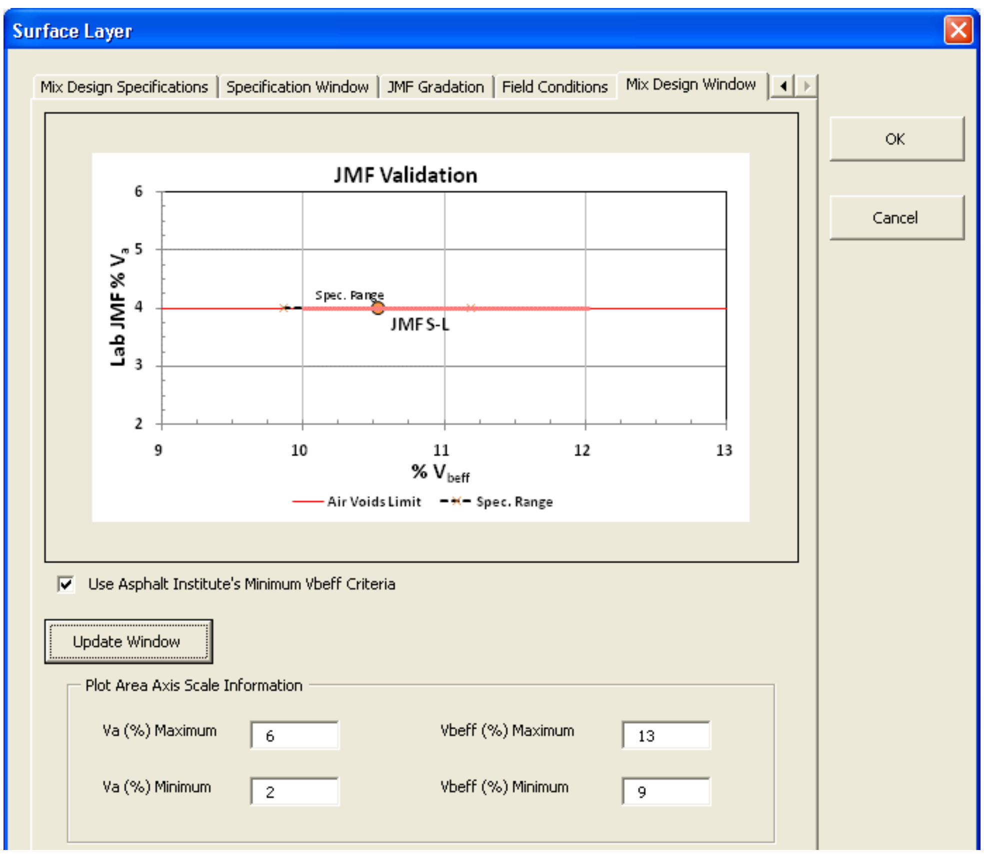



**Figure 30. Example 1 Mix Design Verification screen with Specification Range**

Once all required data are entered in the program, the program is run for each distress by clicking on the appropriate blue buttons, as shown in the main input screen (Figure 23).

The output plots present (1) solid contour lines of in-situ air voids versus effective binder volume at several levels of predicted distress, (2) a black dot for the target value, (3) a dashed line for the distress criterion, and (4) a window delineated by the in-situ mix limits and tolerance.

Figure 31 shows the predicted HMA rut depth of the surface layer. The program predicts a rut depth of 0.18 inches for the target value (black dot), which is below the specification criterion of 0.2 inches shown as a black dashed line.

Similarly in Figure 32, the predicted value of fatigue cracking is about 11%, which is considerably below the maximum specification criterion of 20%. (In this plot the criterion overlies the 20% fatigue cracking contour but can be seen as a black dashed line.)

Finally, Figure 33 presents the thermal cracking output. The predicted thermal cracking at the target value is about 1,860 feet/mile. This predicted distress exceeds the specified criterion of 1,000 feet/mile. In fact, the distress criterion cannot be seen in the plot since it is far lower than the predicted value. As a result, the mix should be redesigned, perhaps by changing the binder type to a softer grade, increasing the HMA layer thickness, or increasing the binder content of the mix.

In summary, the predicted rut depth and fatigue cracking satisfied both the mix design limits and the distress prediction criteria. However, the predicted thermal cracking failed to satisfy the distress criterion established for the project.

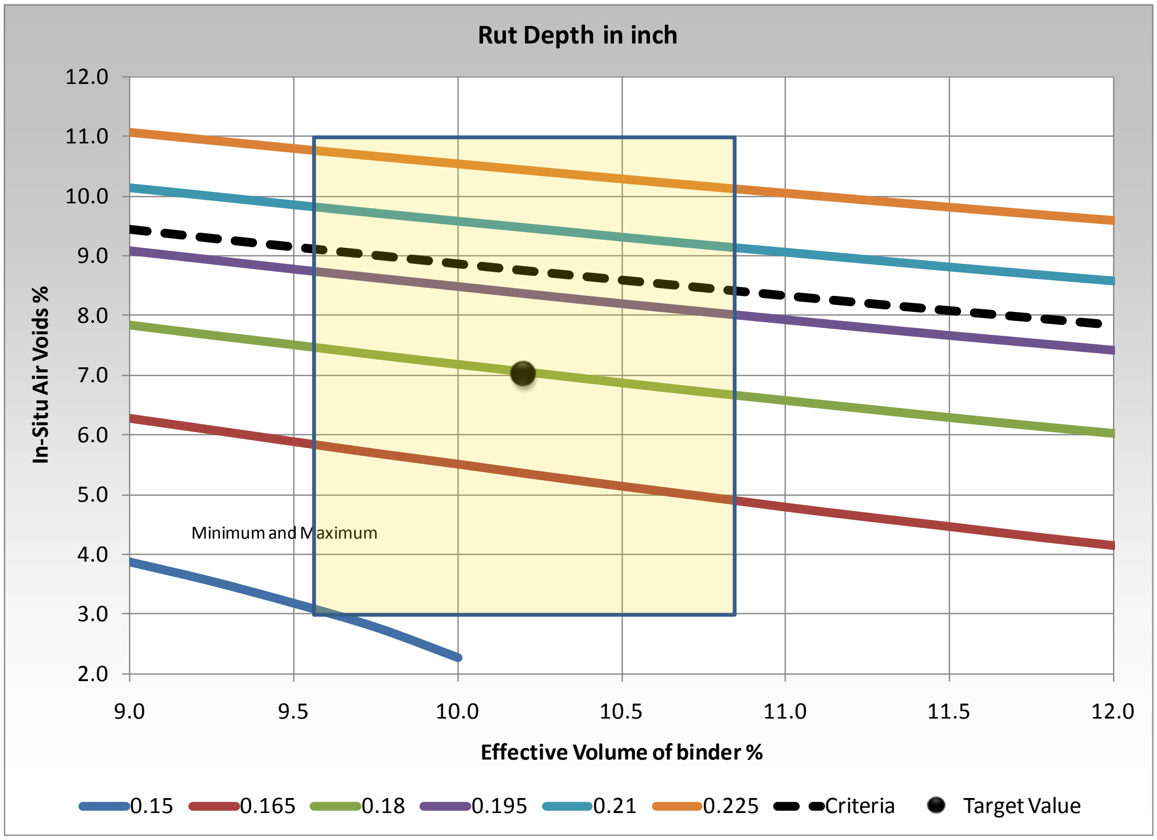



**Figure 31. Example 1 Rut Depth Output**

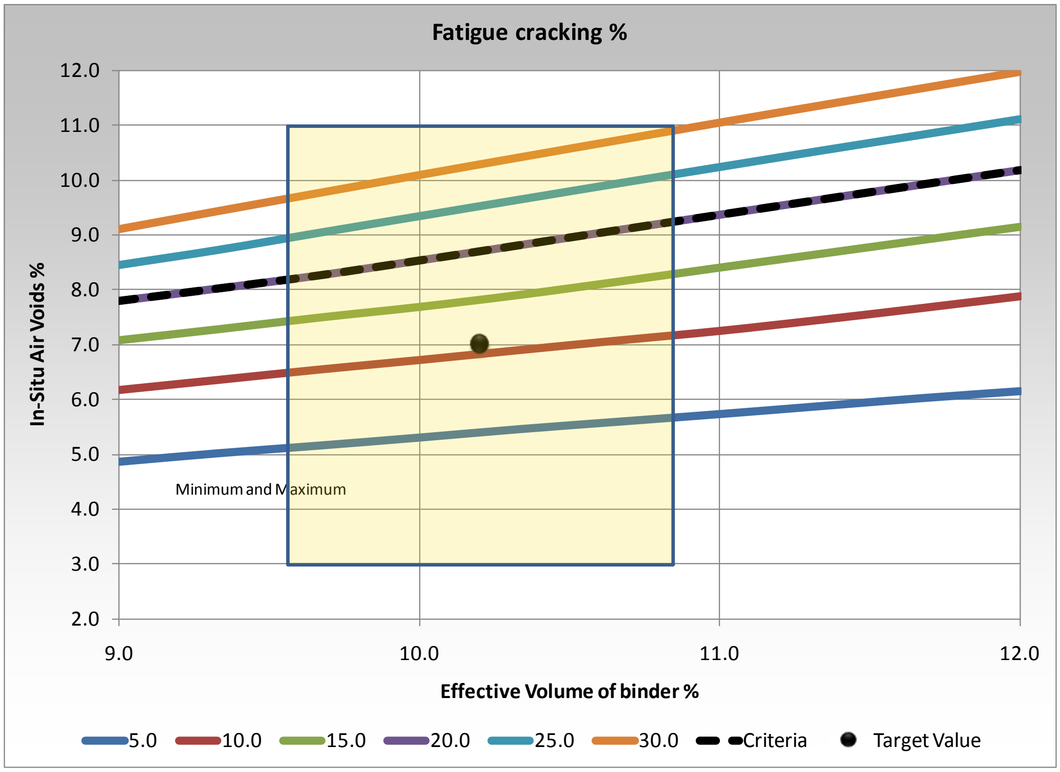



**Figure 32. Example 1 Fatigue Cracking Output**

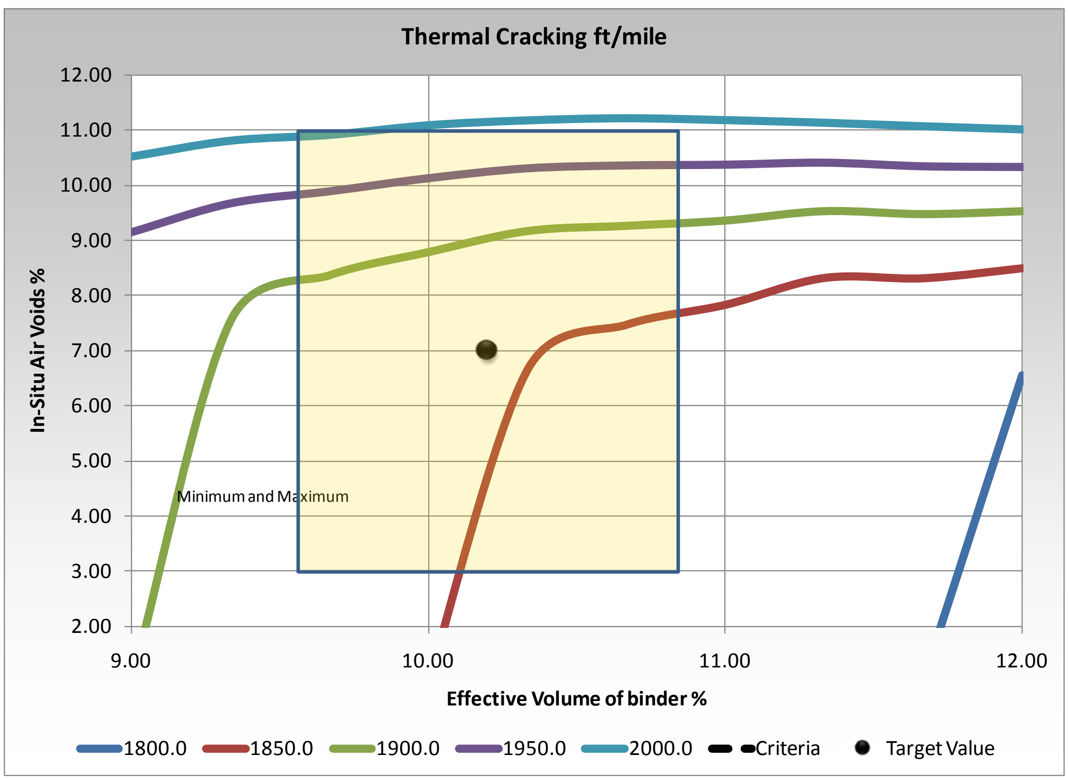



**Figure 33. Example 1 Thermal Cracking Output**

### *5.3 Example 2: Marshall Mix Design Procedure*

Example 2 is similar to Example 1 except that the selected HMA mixture specification is the Asphalt Institute's ½-inch heavy traffic specification with 4% air voids. Also, a viscosity (AC) grade was selected for the asphalt binder instead of the performance grade used in Example 1. The Example 2 data are as follows:

1. Project information:
    a. Project ID = 1
    b. Project Name = Example
    c. City = Bismarck
    d. County =
    e. State = North Dakota
    f. Date of analysis = 10/20/2010
    g. Expected construction date = 7/5/2008 (required for thermal cracking analyses).
2. Traffic data:
    a. Vehicle speed = 60 mph
    b. Design life = 20 years
    c. Initial daily E18KSAL = 500
    d. Traffic growth rate = 1%
    e. Total E18KSAL over the design life = 4,038,527
3. Climate data:
    a. Location = Bismarck Municipal Airport
    b. Mean annual air temperature = 43.68°F
    c. Mean monthly air temperature standard deviation = 20.62°F
    d. Mean annual wind speed = 8.06 mph
    e. Mean annual sunshine = 62.94%
    f. Annual cumulative rainfall depth = 17.87 inches
4. Structure data[2]:
    a. HMA surface layer thickness = 6 inches
    b. Granular base thickness = 6 inches
    c. Granular base modulus = 30,000 psi
    d. Granular subbase thicknesses = 8 inches
    e. Granular subbase modulus = 24,000 psi
    f. Subgrade modulus = 5,000 psi
5. Distress Criteria:
    a. HMA (only) Rut Depth = 0.2 inches
    b. Fatigue Cracking = 20%
    c. Thermal Cracking = 1,000 ft/mile
6. Surface layer Material Properties:

---

[2] The base, subbase and subgrade information are required for fatigue cracking analyses.

a. Binder type: AC 2.5
b. HMA binder content: 5.0%
c. $G_{sb}$ = 2.701
d. $G_{se}$ = 2.741
e. $G_b$ = 1.025
f. Laboratory air voids for HMA selection: 4%
g. Specification: AI ½-inch Heavy Traffic
h. Aggregate gradation (% Passing):
    i. ¾ inch = 100%
    ii. 3/8 inch = 78%
    iii. #4 = 40%
    iv. #200=4.1%
i. Target in-situ Air Voids: 7%
j. In-situ air voids limits: ±4%
k. Calculated in-situ effective binder volume ($V_{beff}$) = 10.2 %
l. Construction tolerance: ±0.3% (by weight of mix)

Figure 34 shows the input screen for Example 2. The inputs in this screen are generally the same as Example 1 except for the difference in asphalt binder grade (AC versus PG), which arises from the change in HMA specification type from Superpave to Marshall.

Figure 36 illustrates the key difference between the two examples where the Asphalt Institute's ½-inch heavy traffic with 4% air voids is selected as the mix specification. In this specification the limits on the laboratory air voids used to select the binder content in the JMF are from 3% to 5%. These limits are clearly reflected in the mix window verification in Figure 37.

Figure 37 illustrates the acceptance window for the mix design. Any mix design lying within this window will be accepted by the specification. The graph shows several pieces of critical information, such as the minimum value for the effective binder volume, which is function of the aggregate size. This effective binder volume serves as an excellent lower limit to insure that the mixture has adequate durability. The graph also shows the VFA and minimum VMA limits that establish the dimensions of the window.

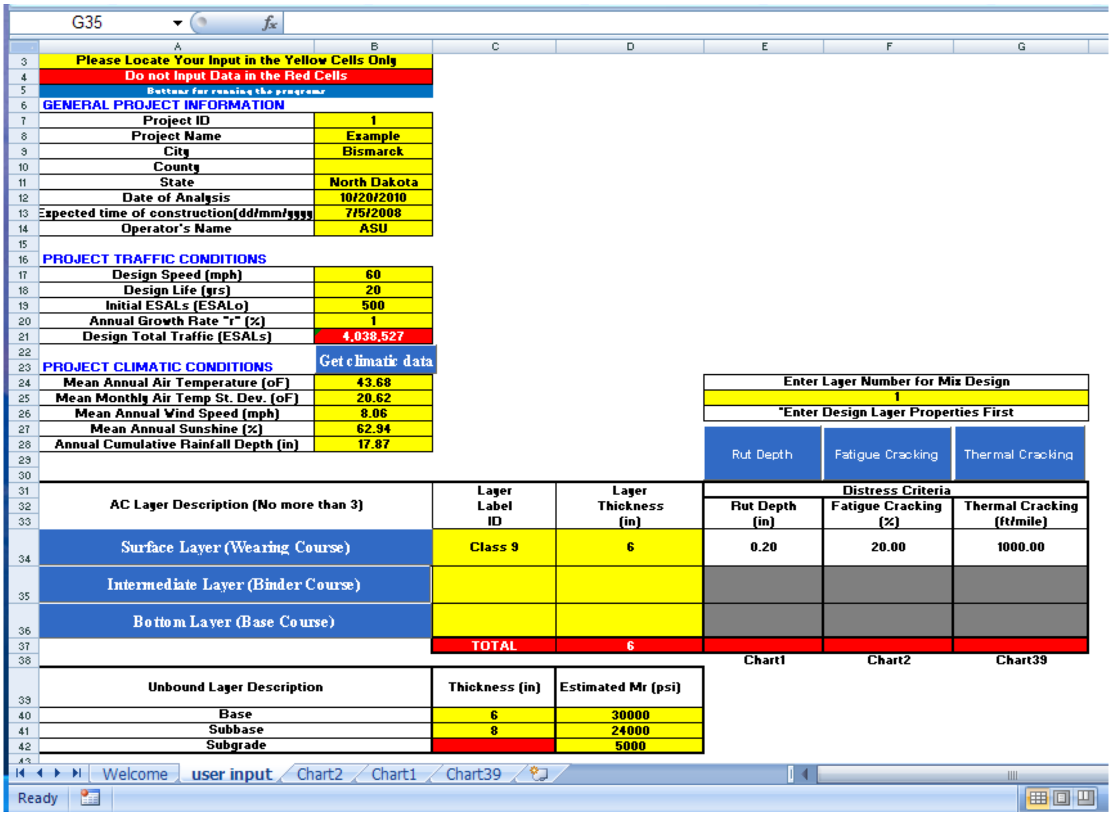



**Figure 34. Example 2 User Input Screen**

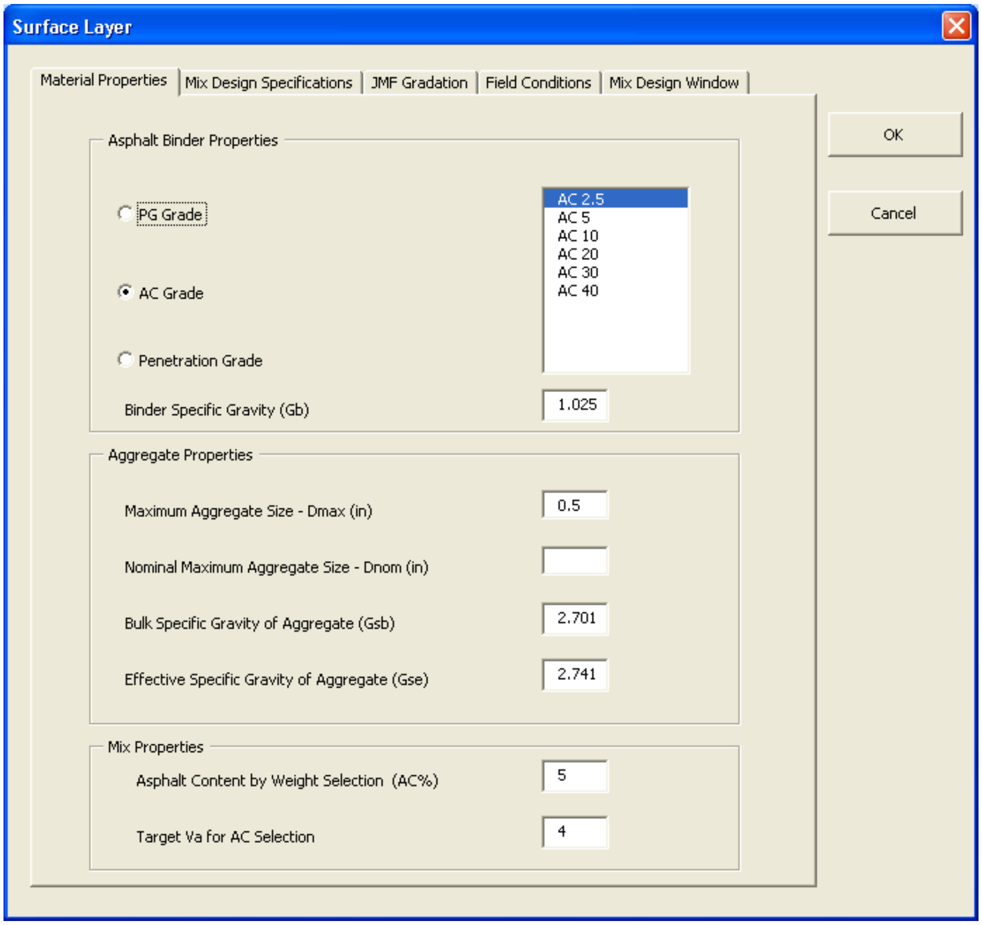



**Figure 35. Example 2 Materials Input Screen**

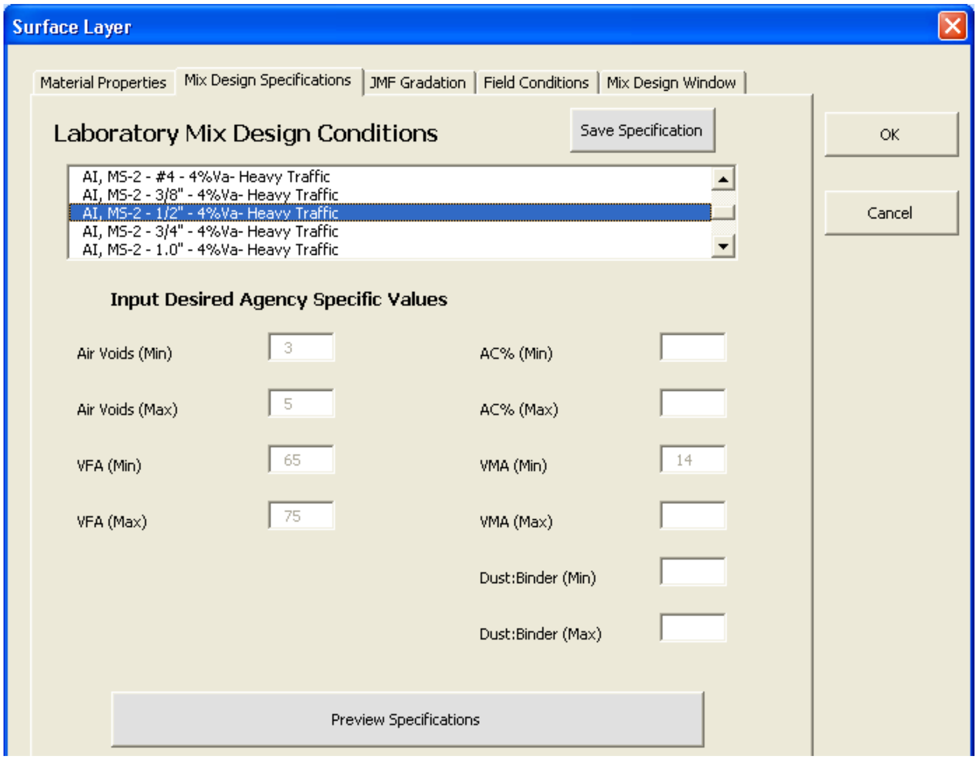



**Figure 36. Example 2 Mix Specification Selection Screen**

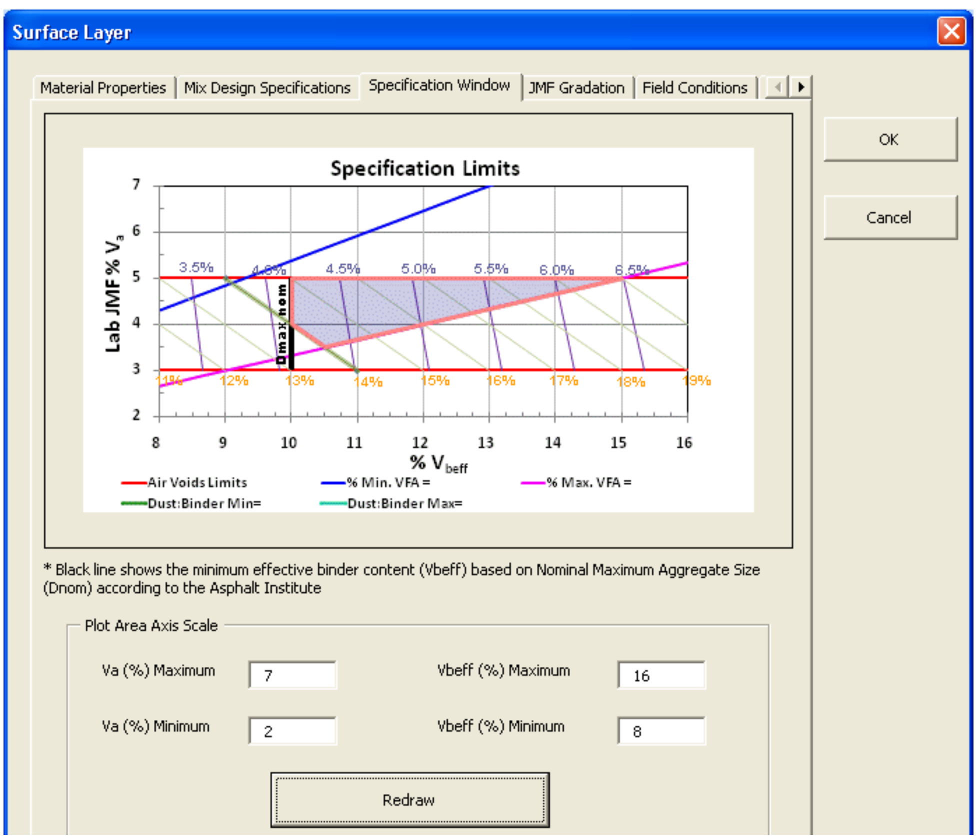



**Figure 37. Example 2 Mix Verification Window Screen**

Figure 38 shows the aggregate gradation of the surface layer. Figure 39 shows the in-situ properties and tolerance of the mix. Finally, Figure 40 shows the mix verification window, but in contrast to Figure 37, only the borders of the mix verification window are presented. Figure 40 also shows the target mix design and the specification range.

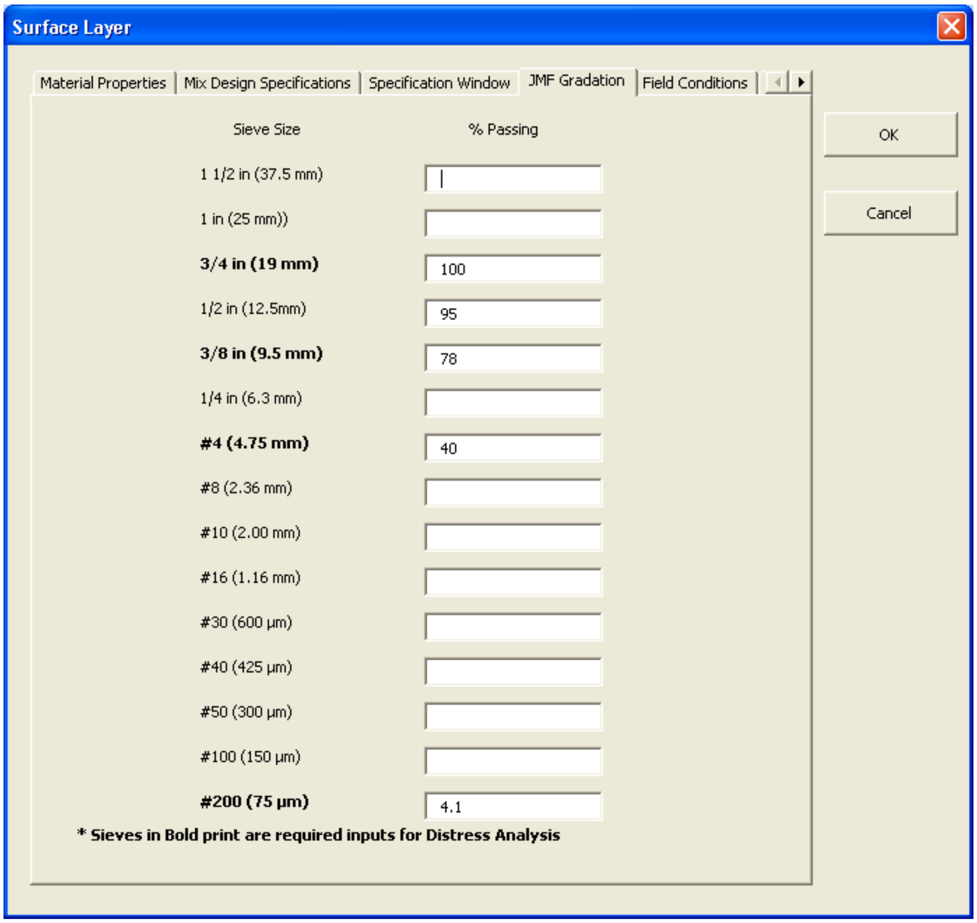



**Figure 38. Example 2 Aggregate Gradation Input Screen**

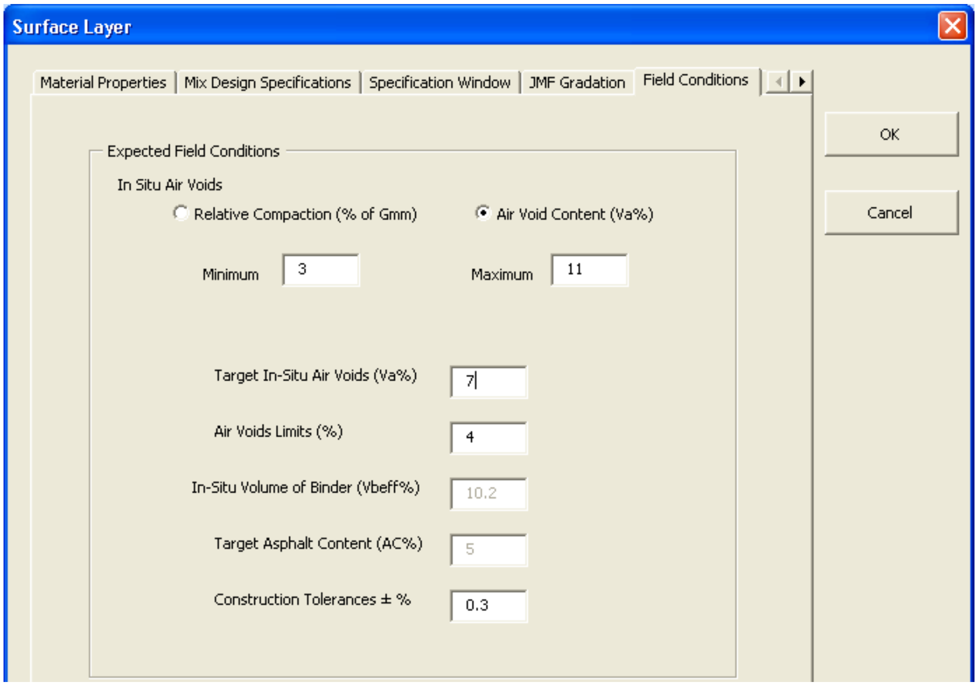



**Figure 39. Example 2 In-situ Properties Input Screen**

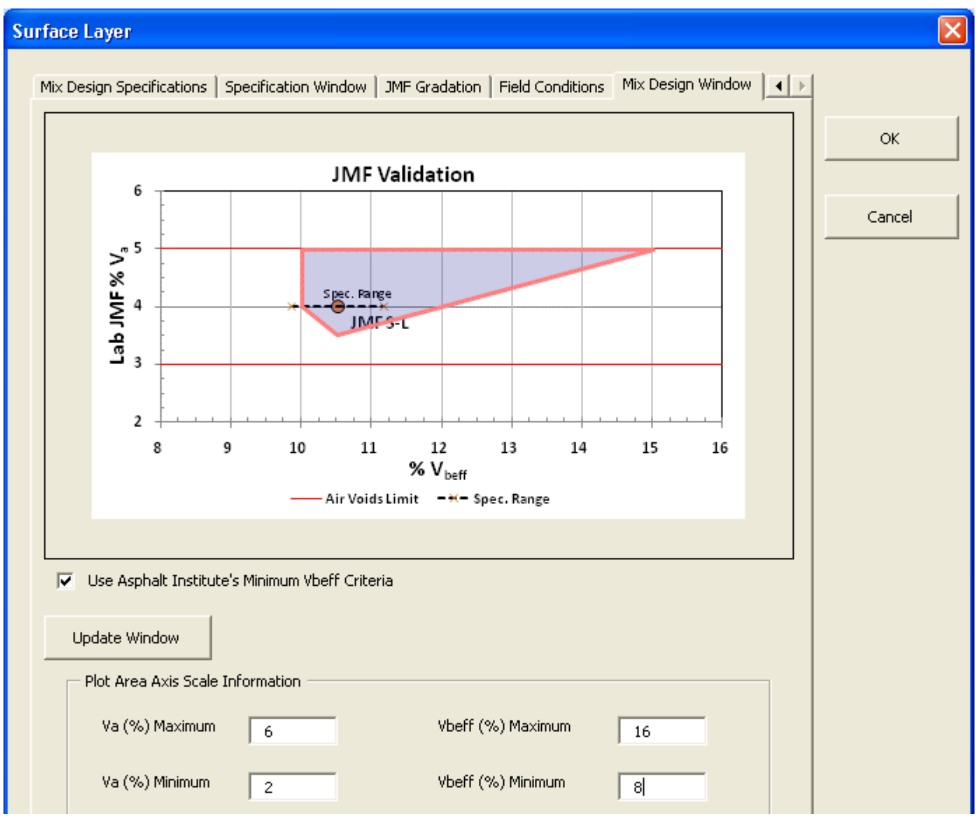



**Figure 40. Example 2 Mix Verification Window Screen with Specification Limits**

Once the mix design is accepted, the distress analysis is run to predict the three distresses. Figure 41 shows that the predicted rut depth meets the rutting distress criterion. Similarly, Figure 42 shows that the predicted fatigue cracking is below the fatigue cracking criterion set as an upper limit.

Figure 43 shows that the predicted thermal cracking is less than that in example 1 since a much softer binder was used. However, the predicted thermal cracking still fails the distress criterion, suggesting that further adjustments to the binder grade or other changes to the mix or structural designs would be necessary.

To return to the mix design to adjust the binder content and rerun the distress prediction analysis, the blue button for each distress is clicked. These new distress predictions must then be compared to the distress criteria.

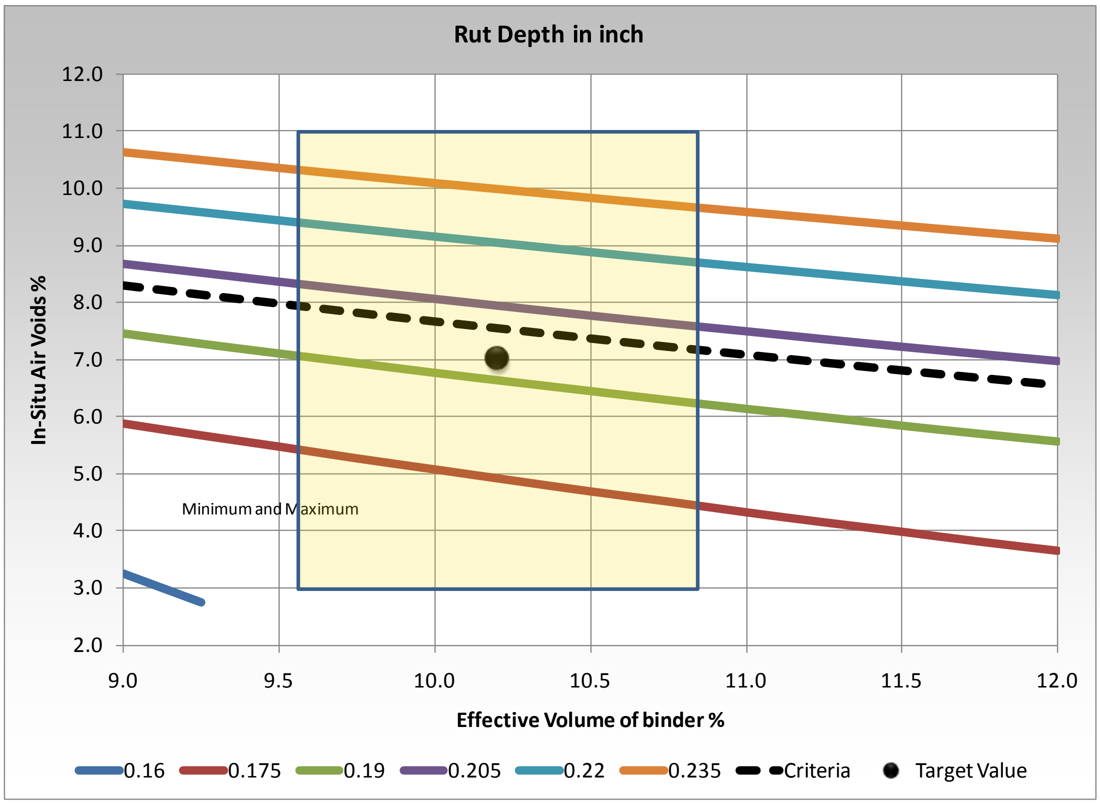



**Figure 41. Example 2 Rut Depth Output**

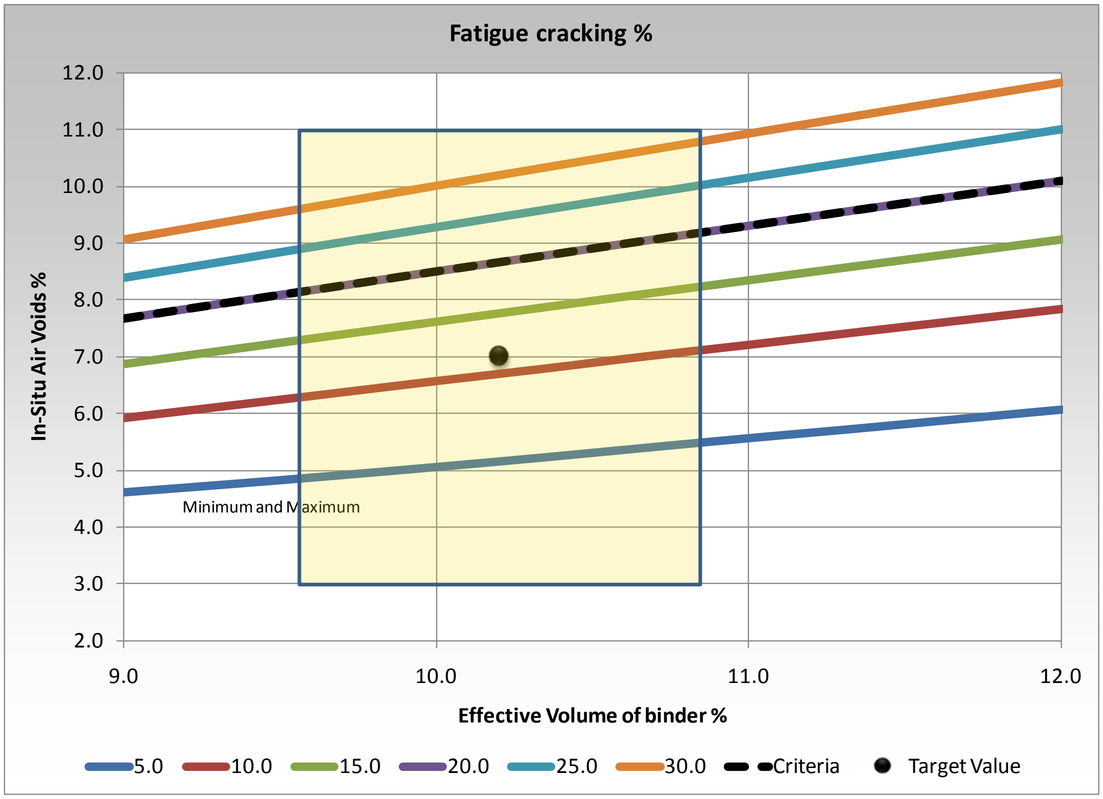



**Figure 42. Example 2 Fatigue Cracking Output**

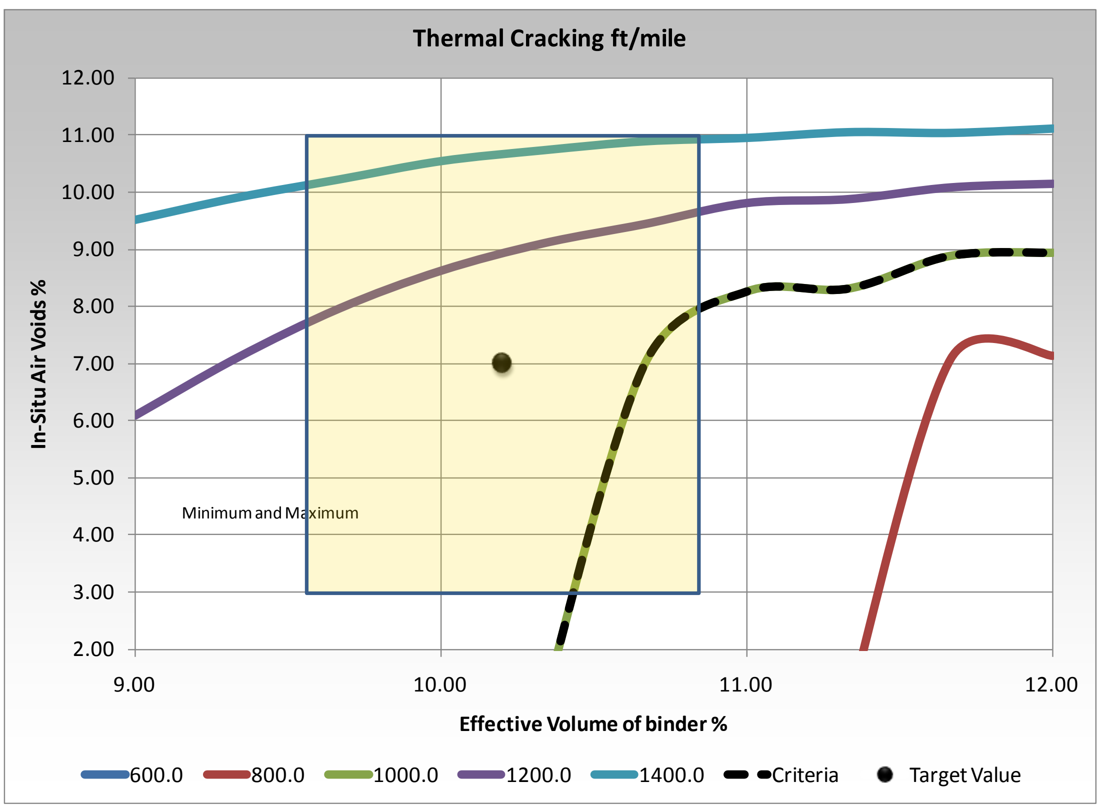



**Figure 43. Example 2 Thermal Cracking Output**

**REFERENCES**

1. Transportation Research Board, "Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures," Project Final Report, NCHRP Project 1-37A, "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II." Online. Available at http://www.trb.org/mepdg. Accessed 29 November 2010.

1a. Transportation Research Board, NCHRP Project 9-19, "Superpave Support and Performance Models Management." Online. Available at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=955. Accessed 29 November 2010.

1b. Transportation Research Board, E* SPT Specification Criteria Program. Online. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP09-19_E-starSpecCriteria.xls. Accessed 29 November 2010.

2. Transportation Research Board, NCHRP Project 9-22, "Beta Testing and Validation of HMA PRS." Online. Available at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=958. Accessed 29 November 2010.

2a. Transportation Research Board, Interdependent Analysis Program for HMA Mix and Structural Designs. Online. Available at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2406.

2b. Bari, J. and M.W. Witczak. Development of a New Revised Version of the Witczak E* Predictive Model for Hot Mix Asphalt Mixtures, *Journal of the Association of Asphalt Paving Technologists*, Vol. 75, 2006.

3. Superpave Mix Design. Manual Series SP-2, Third Edition, Asphalt Institute, Lexington, Kentucky, Revised 2001.

4. Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types. Manual Series MS-2, Sixth Edition, Asphalt Institute, Lexington, Kentucky, 1994.

4a. McLeod, N.W. Relationship Between Density, Bitumen Content, and Voids Properties of Compacted Paving Mixtures, *Proc. Highway Research Board*, Vol. 35, 1956.

4b. Coree, B.J. Hot-Mix Asphalt Volumetrics Revisited: A New Paradigm, *Transportation Research Record*, Vol. 1681, 1999.

5. Sotil, A. "Use of the Dynamic Modulus E* Test as Permanent Deformation Performance Criteria for Asphalt Pavement Systems", Ph.D. Dissertation, Arizona State University, Tempe AZ, 2005.

5a. Transportation Research Board. Mechanistic-Empirical Pavement Design Guide Software Version 1.1. Online. Available at http://onlinepubs.trb.org/onlinepubs/archive/mepdg/software.htm. Accessed 30 November 2010.

6. Witczak, M.W. "Specification Criteria for Simple Performance Tests for Rutting, Volume I: Dynamic Modulus (E*), Volume II: Flow Number and Flow Time", NCHRP Report 580, Transportation Research Board of the National Academies, Washington D.C., 2007.

7. Witczak, M.W., El-Badawy, S. and Jeong, M.G. "Development of a Rational Methodology to Assess Performance Related Pay Factors for Load associated Alligator Fatigue Cracking", Project Interim Status Report No. 3, Arizona State University, Tempe, AZ, September 2006.

8. Witczak, M.W., Roque, R., Hiltunen, D.R., and Buttlar, W.G. "Project Deliverable B, Modification and Re-Calibration of Superpave Thermal Cracking Model", PDF File 11-E, CRP-CD-46, "Appendixes to NCHRP Report 547: Simple Performance Tests and Advanced Materials Characterization Models," Transportation Research Board, Washington DC, 2005.