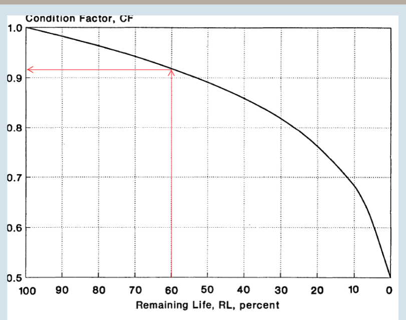
National Concrete Pavement Technology Center

Guide to the Design of Concrete Overlays Using Existing Methodologies



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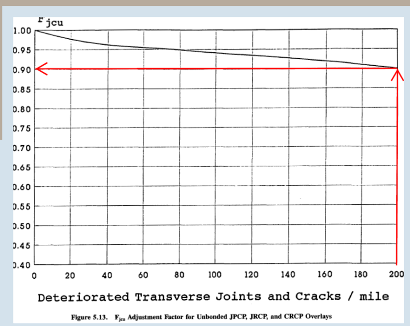

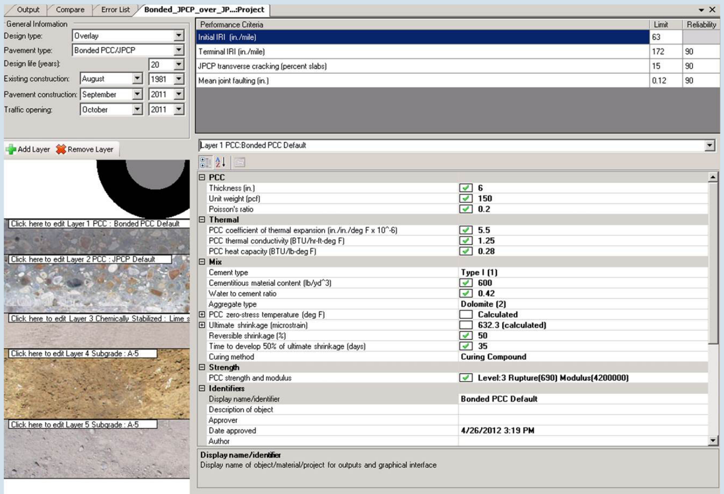

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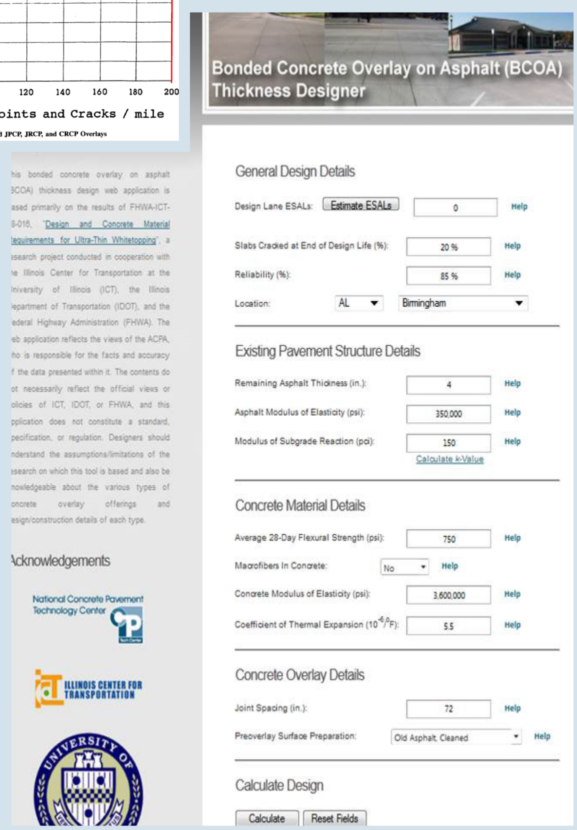
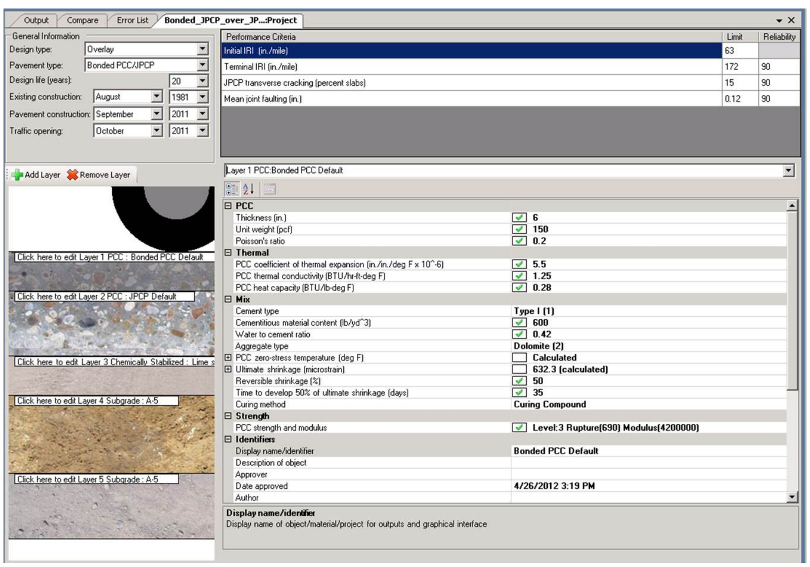


Bonded Concrete Over Asphalt (BCOA)

Iowa State University
Institute for Transportation

October 2012

On the Cover



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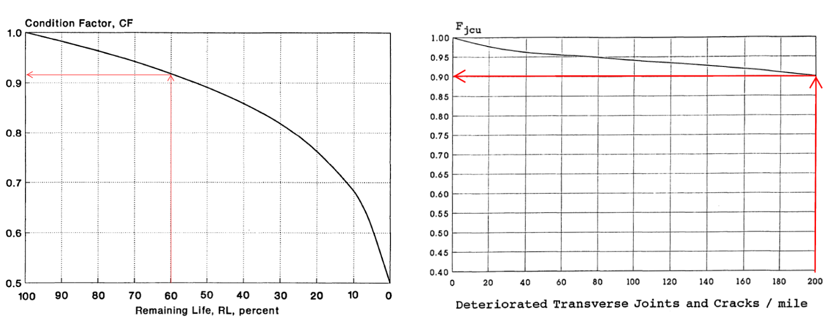
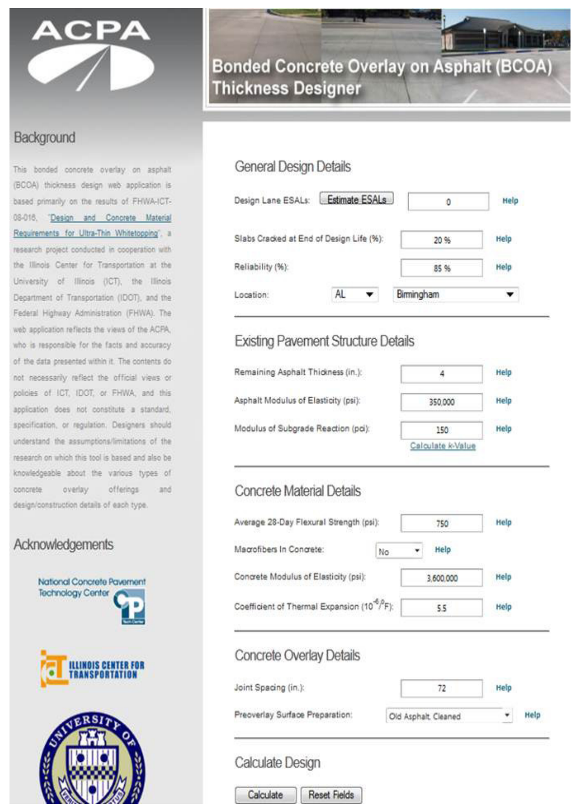


1993 AASHTO Guide for Design of Pavement Structures (1993 AASHTO Guide), nomographs



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16. Abstract

The Guide to the Design of Concrete Overlays Using Existing Methodologies is a product of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University's Institute for Transportation. The guide provides decision makers and practitioners with straightforward, simple guidance for the design of concrete overlays using existing methodologies.

- The guide focuses on four commonly used methods:
- The method described in the 1993 AASHTO *Guide for Design of Pavement Structures*, 4th Edition.
- The method described in the AASHTO *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice*.
- The ACPA modified method for bonded concrete overlays of asphalt pavements.
- The Colorado Department of Transportation method for bonded concrete overlays of asphalt pavements.

The guide discusses specific design assumptions, deficiencies, and strengths inherent in each method, as well as step-by-step design examples for typical pavement sections that are viable concrete overlay candidates.

This guide is intended to be used in conjunction with the corresponding design procedures' documentation/references, such as the 1993 AASHTO Guide for Design of Pavement Structures and/or computer software for the AASHTO Mechanistic-Empirical Pavement Design Guide and ACPA methods.

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Guide to the Design of Concrete Overlays Using Existing Methodologies

FHWA Project DTFH61-06-H-00011 (Work Plan 13)

October 2012

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About This Guide

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Disclaimers

Mission

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement stakeholders around the central goal of advancing concrete pavement technology through research, technology transfer, and technology implementation.

National Concrete Pavement Technology Center

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Figure 1 from Harrington et al. 2008, *Guide to Concrete Overlays*, courtesy of the National Concrete Pavement Technology Center.

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Figures 6, 7, 18-26, 33-38, 40-46, 49-56, 59-65 represent screen captures from AASHTOWare Pavement ME Design software (formerly DARWin-ME software).

Figures 9, 28, 30 represent screen captures from the ACPA BCOA web application (http://apps.acpa.org/apps/bcoa.aspx).

Figure 11 courtesy of the Missouri/Kansas ACPA.

Figure 12 from ACPA Technical Bulletin TB-005P, *Guidelines for Concrete Overlays*.

Figures 16, 17, 32, 48, 58 from 1993 AASHTO *Guide for Design of Pavement Structures, 4th Edition*.

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GUIDE to the Design of

CONCRETE OVERLAYS

Using Existing Methodologies

October 2012

1. Introduction

In recent years, there has been an increasing drive for more viable pavement maintenance and rehabilitation options (as opposed to new design). With an ever-aging road network and tight budgets, the prospects of a large-scale reconstruction program are not realistic. In many pavement rehabilitations, concrete overlay alternatives may be a more cost-effective, rapidly constructed, and sustainable option than full reconstruction.

Over the years, concrete overlay design procedures have been developed by a number of agencies, including the American Association of State Highway and Transportation Officials (AASHTO), the National Cooperative Highway Research Program (NCHRP), the Portland Cement Association (PCA), the American Concrete Pavement Association (ACPA), and various State departments of transportation (DOTs). Each method addresses different types of concrete overlays and involves different inputs, software, strengths, and deficiencies.

The goal of this guide is to provide straightforward and simple guidance for concrete overlay design using existing methodologies. The first section presents an overview of the concrete overlay design process and identifies some of the more sensitive variables inherent in four different procedures:

1. The method described in the 1993 AASHTO *Guide for Design of Pavement Structures*, 4th Edition (1993 AASHTO Guide).
2. The method described in the AASHTO *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice* (AASHTO Pavement ME Design Guide*).
3. The ACPA modified method for bonded concrete overlays of asphalt pavements (ACPA BCOA).
4. The Colorado Department of Transportation (CDOT) method for bonded concrete overlays of asphalt pavements.

*Footnote: The shorthand "AASHTO Pavement ME Design Guide" is based on "AASHTO Ware Pavement ME Design," the 2012 edition of AASHTO's Mechanistic-Empirical Pavement Design Guide software.

In addition, the first section of this guide includes an overview of the work currently being conducted as part of Transportation Pooled Fund Study TPF-5(165), Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements, led by the Minnesota Department of Transportation (Mn/DOT) to develop a design procedure for BCOA. This and other ongoing work exemplify how concrete overlay design is a dynamic field; there is ongoing work throughout the industry to advance current procedures and develop new ones.

In this guide, specific design assumptions, deficiencies, and strengths inherent in each method are discussed, with the intent to describe the state of the practice in concrete overlay design. Based on this information, the bulk of the guide provides step-by-step design examples for typical pavement sections today that are viable concrete overlay candidates. The ultimate goal of this document is to offer designers the necessary background information and guidance to effectively design concrete overlays. This guide is intended to be used in conjunction with the corresponding design procedures' documentation/references, such as the 1993 AASHTO *Guide for Design of Pavement Structures*, 4th Edition, and/or computer software for the AASHTO Pavement ME Design and ACPA methods.

The information presented in this guide is specific to concrete overlay design and focuses on thickness design in particular. Designers who desire detailed information and guidance on the various concrete overlay types, the selection process, pre-overlay repair requirements, materials, construction techniques, and maintenance expectations should consult the *Guide to Concrete Overlays* (Harrington et al. 2008).

Concrete overlays can be used to rehabilitate all existing pavement types exhibiting various levels of deterioration. The *Guide to Concrete Overlays* (Harrington et al. 2008) categorizes all concrete overlays into two main types: bonded and unbonded (figure 1).

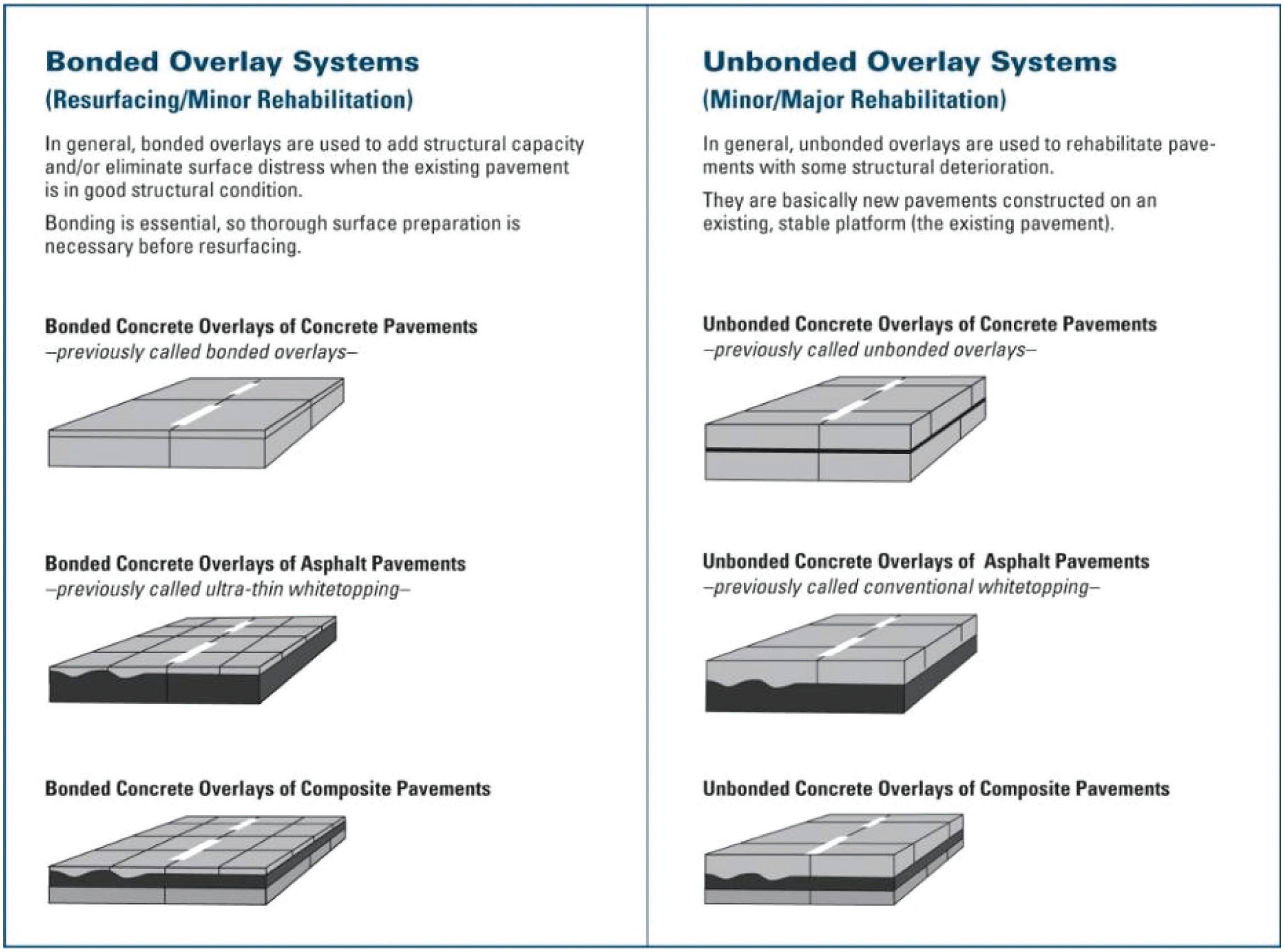

Figure 1. Bonded and Unbonded Concrete Overlay Systems (Harrington et al. 2008).

1.1 Overview of Bonded Concrete Overlays

Bonded concrete overlays over existing concrete, asphalt, and composite pavements are used to restore the structural capacity and/or to correct surface defects of existing pavements that are in fair to good condition. These overlays commonly range between 2 and 6 in. in thickness (figure 2) and rely on the assumption of a long-term physical bond between the overlay and the existing surface to create a monolithic pavement layer. Special attention to surface preparation activities is essential to ensure a clean pre-overlay surface and to provide an appropriate macrotexture level for bonding. Furthermore, to minimize the potential for reflective cracking, pre-overlay repairs may be required to address severe cracking, spalling, patches, punchouts, pumping/faulting, and/or settlement/heaving in the existing pavement. Bonded overlays are not feasible if the existing pavement requires significant removal and replacement, if durability problems are present, or if vertical clearance limitations exist.

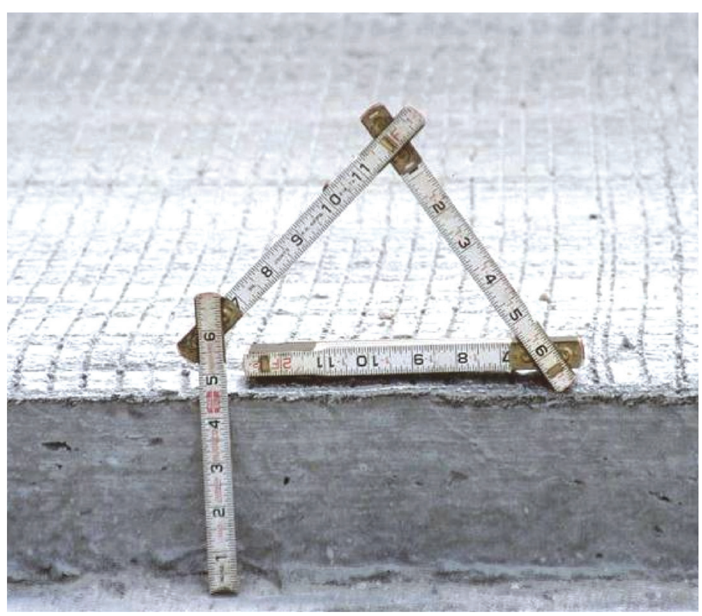

Figure 2. Bonded Concrete Overlay, 4.5 in. Thick.

1.2. Overview of Unbonded Concrete Overlays

Unbonded concrete overlays over existing concrete, asphalt, and composite pavements are commonly used to address moderately to severely distressed pavements. In this case, the existing pavement provides a foundation for the unbonded overlay that, in turn, serves as a new pavement with increased structural capacity. Unbonded overlays over existing concrete pavements require a separation layer to prevent reflective cracking by providing a shear plane for differential movements and to prevent bonding between the concrete layers. Figure 3 shows the application of an asphalt separation layer to an existing concrete pavement exhibiting faulting and longitudinal displacement/slab slippage. Unbonded overlays over existing asphalt or composite pavements require little or no surface preparation and typically do not require an additional separation layer. These unbonded overlays typically range between 4 and 11 in. in thickness and are most cost-effective when the pre-overlay repairs can be minimized by placing a separation layer of a certain thickness or type.

2. Background of Design Methodologies

Designing either bonded or unbonded concrete overlays is a process that begins with characterizing the existing pavement, defining critical design variables, and then calculating the required overlay thickness. This section presents a general overview of the four design methodologies discussed in this guide:

1. The 1993 AASHTO Guide (Section 2.1).
2. The AASHTO Pavement ME Design Guide (Section 2.2).
3. The ACPA BCOA (Section 2.3).
4. The CDOT method for bonded concrete overlays of asphalt pavements (Section 2.4).

In addition, Section 2.5 outlines an ongoing effort to develop a new methodology for bonded concrete overlay designs over asphalt pavements: Federal Highway Administration (FHWA) Pooled Fund TPF-5(165), Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements.

2.1. 1993 AASHTO Guide Method

The method found in the 1993 AASHTO Guide is based on mathematical models derived from empirical data collected during the American Association of State Highway Officials (AASHO) Road Test carried out in the late 1950s. Even though no overlay sections were evaluated during the AASHO Road Test, experience has shown that, when used properly, this procedure provides suitable bonded and unbonded concrete overlay designs. The AASHTO computer software for implementing the 1993 AASHTO Guide is called DARWin. In addition, a number of agencies and State DOTs have developed custom software and spreadsheets to apply this procedure. ACPA has also developed the WinPAS software package, which implements the procedure.

The 1993 AASHTO Guide uses the concepts of structural deficiency and effective structural capacity for evaluating and characterizing the existing pavement to be overlaid. The structural capacity (SC) of a pavement section decreases with traffic and time. In this procedure, SC is expressed in terms of the effective structural number for existing asphalt pavements (SN_{eff}), or the effective slab thickness for concrete pavements (D_{eff}). Figure 4, which is an adaptation of figure 5.1 in Part III of the 1993 AASHTO Guide, illustrates this concept. This figure illustrates how the structural capacity of an overlay ($SC_{overlay}$) restores the structural capacity of the existing pavement ($SC_{effective}$) to meet the requirements for carrying the predicted future traffic ($SC_{future\ traffic}$).

Figure 3. Application of Asphalt Separation Layer to Existing Concrete Pavement for Unbonded Concrete Overlay.

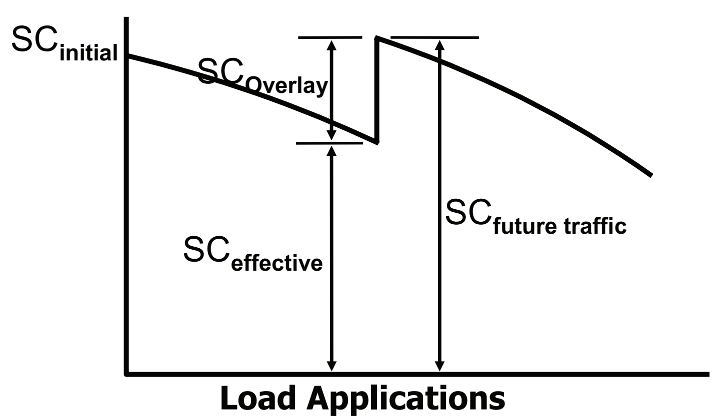

Figure 4. Illustration of Structural Capacity Loss over Time and with Traffic.

The 1993 AASHTO Guide presents three evaluation methods for determining the effective structural capacity of existing pavements (SC_{eff}) when designing concrete overlays: Visual Survey and Materials Testing (Condition Survey), Nondestructive Deflection Testing (NDT), and Fatigue Damage from Traffic (Remaining Life). The designer should select the most feasible method based on the available resources but should recognize that each method yields different estimates. Table 1 presents a summary of the three AASHTO evaluation methods as they apply to concrete overlays.

Even though the Remaining Life method presented in table 1 is often used, it is important to note that the 1993 AASHTO Guide cites major deficiencies associated with this method and explains that the method is mostly applicable when the existing pavement exhibits very little deterioration. The 1993 AASHTO Guide explains that the Remaining Life procedure is based on the AASHO Road Test equations, and estimating past traffic (in equivalent single axle loads [ESALs]) may be subjective and/or uncertain. In addition, this method does not account for pre-overlay repairs. For these reasons, the designer should use the Condition Survey method or Nondestructive Deflection Testing when the structural capacity estimates that result from the Remaining Life method are inconsistent with the observed existing pavement condition.

2.2. AASHTO Pavement ME Design Guide Method

The AASHTO Pavement ME Design Guide procedure was developed under NCHRP project 1-37A, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures, and the original guide and accompanying software were both called the Mechanistic-Empirical Pavement Design Guide (M-E PDG). At this time, the original M-E PDG document is still available online at www.trb.org/mepdg, while the M-E PDG software is no longer available. This guide is now officially implemented by AASHTO, and the main reference document is the AASHTO *Mechanistic-Empirical Pavement Design Guide, Interim Edition: A Manual of Practice* (AASHTO 2008). The procedure is implemented in an AASHTO professional software package called *AASHTOWare Pavement ME Design*, available at http://www.aashtoware.org.

The AASHTO Pavement ME Design Guide procedure combines a mechanistic-based approach with field performance data so that an engineer can confidently predict the performance of pavement systems not considered in the original calibration . This method adopts an integrated pavement design approach that allows the designer to determine the overlay thickness based on the interaction between the pavement geometry (slab size, shoulder type, load transfer, steel reinforcement), local climatic factors, and concrete material and support layer properties. The procedure is currently under evaluation and implementation by a number of State DOTs.

Chapter 7 in Part 3 of the M-E PDG (NCHRP 2004), "PCC [Portland Cement Concrete] Rehabilitation Design of Existing Pavements," contains detailed information regarding the design of bonded and unbonded concrete overlays. This procedure is an iterative design process that involves analyzing a trial overlay design not only in terms of thickness but also in terms of other relevant design features, such as joint dimensions and load transfer, steel reinforcement (if applicable), and concrete material properties. The following list summarizes the AASHTO Pavement ME Design Guide inputs (NCHRP 2004):

- Rehabilitation type.
- Design life.
- Pavement failure criteria (cracking, faulting, International Roughness Index [IRI]).
- Reliability.

Table 1. Summary of 1993 AASHTO Guide Methods to Evaluate Effective Structural Capacity of Existing Pavements to Receive a Concrete Overlay.

Method	Description
Visual Survey and Materials Testing (Condition Survey)	Condition assessment based on historical records, distress and drainage surveys, and coring and material testing. The pavement layer thicknesses and conditions are determined through coring or ground penetrating radar. Typical laboratory testing of the portland cement concrete (PCC) cores involves strength tests. Correlations with compressive strength are typically used to estimate the existing slab elastic modulus and modulus of rupture. If a bonded overlay will be used, areas that will require repairs or full-depth repairs are identified to ensure a sound and uniform section before the bonded overlay is applied.
Nondestructive Deflection Testing (NDT)	Direct evaluation of in situ subgrade and pavement stiffness along a project. NDT also allows for evaluating the pavement layer load transfer efficiency, effective modulus of subgrade reaction, and elastic modulus. The majority of state highway agencies and number private engineering companies have the required equipment and personnel available.
Fatigue Damage from Traffic (Remaining Life)	Estimate of a pavement's remaining fatigue life based on past traffic. This method requires estimating traffic in terms of ESALs, both the ESALs accumulated to date and the total expected ESALs that the pavement will carry. Note that the Remaining Life method is only applicable to pavements with very little deterioration. In addition, this method applies only to bonded and unbonded overlays of existing concrete pavements and does not apply to unbonded overlays of composite and asphalt pavements.

- Traffic.
- Local climate.
- Pavement cross-section and layer properties.
- Pavement design features.
    - Slab geometry.
    - Joint and shoulder type.
    - Concrete properties (strength, mixture proportions, coefficient of thermal expansion [CTE], etc.).
    - Drainage and surface properties.

Three input levels are available for pavement design, depending on the quality of the input data. Level 1 inputs are used if project-specific traffic data are available and if certain pavement layer material properties have been measured. Level 2 inputs are used if correlations with standard tests are necessary to complete the design. Level 3 inputs assume national default values in the design process. This document emphasizes Level 2 and 3 inputs as a recommended starting point for using the AASHTO Pavement ME Design Guide procedure.

The AASHTO Pavement ME Design Guide method predicts performance indicators, such as IRI, transverse cracking, and mean joint faulting, over the pavement's design life for jointed plain concrete overlays. For continuously reinforced concrete overlays, the procedure predicts the mean crack spacing as well as crack width, IRI, and number of punchouts over the design life. For all of the distress predictions, the AASHTO Pavement ME Design method calculates incremental damage over the life of the pavement by employing transfer functions for the specific distresses, which are linked with the corresponding maximum pavement response (deflection or tensile stress).

2.3. ACPA BCOA Method

ACPA (1998) developed a mechanistic procedure to design thinner (2 to 4 in.) bonded concrete overlays of asphalt pavements with smaller slab sizes, which are not captured by the two AASHTO methods described above. This BCOA method consists of an iterative design process, where the designer evaluates the proposed overlay thickness and joint spacing along with traffic, concrete strength (modulus of rupture), existing asphalt concrete thickness, and composite subgrade/subbase stiffness (k-value). The procedure determines the allowable trucks for the trial design.

The ACPA procedure is based on calculating the fatigue damage in the slab for a corner loading condition, as well as limiting the fatigue damage at the bottom of the existing asphalt pavement at the transverse joint location (ACPA 1998). Temperature curling stresses are also considered in the critical pavement response. One limitation of this method is that it is based on the PCA beam fatigue model, which yields very conservative estimates. As a result, Riley developed a modified ACPA method in 2006 that incorporated a new probabilistic concrete fatigue algorithm (Riley et al. 2005). This modified method allows for inputting the existing asphalt pavement properties, accounts for the type and amount of structural fibers, and checks for a potential bond plane failure.

In January 2011, ACPA released a BCOA thickness design web application (http://apps.acpa.org/apps/bcoa.aspx) that incorporates the work by Riley (2006). The ACPA BCOA is valid for a slab thickness of 3 to 6 in. and a maximum panel size of 6 ft. Shorter joint spacings (both transverse and longitudinal) are typically used for bonded overlays over asphalt pavements, such as 4 ft by 4 ft or 6 ft by 6 ft slabs for a 12 ft wide lane. Note that the ACPA BCOA web application does not allow designs outside these ranges and provides warnings to indicate that the trial design needs to be modified or that a bonded overlay of asphalt pavement may not be the appropriate solution. Furthermore, when BCOA designs are approaching 6 in. thick and 6 ft wide, the CDOT and TPF-5(165) procedures described in the next two sections should be considered.

Updates in 2012 improved the fiber reinforcement input to the ACPA BCOA based on work by Roesler et al. (2008), which used the residual strength ratio of the fiber reinforced concrete measured according to ASTM C1609-10. In 2012, the BCOA design tool was also upgraded to allow for structural designs in any climate zone in the U.S. by including site-specific effective temperature gradients (Vandenbossche et al. 2012) for approximately 200 cities.

The input requirements for the ACPA BCOA thickness design tool are as follows:

- ESALs.
- Percentage of allowable cracked slabs.
- Reliability.
- Design location (to determine the site specific effective temperature gradient).
- Existing asphalt pavement:
    - Remaining asphalt thickness and modulus.
- Composite subgrade/subbase k-value.
- Concrete overlay:
    - Strength, modulus, fiber residual strength ratio, and CTE.
- Proposed slab size and pre-overlay surface preparation.

The recent implementation of the effective temperature gradient for each city was determined as the equivalent negative temperature gradient that gives the same cumulative damage as the full distribution of temperature differentials for that particular site and inputs (slab thickness, slab length, asphalt thickness, and concrete strength). For all site locations, this effective temperature gradient occurs 100 percent of the time to give the same fatigue damage as the full temperature differential distribution.

2.4. CDOT Method

CDOT developed a mechanistic procedure to design bonded concrete overlays of asphalt pavements ranging from 4 to 8 in. thick with joint spacings up to 12 ft. The procedure is intended for moderate- or high-volume traffic roadways such as State routes and U.S. highways. This method is based on a 1998 study (Tarr et al. 1998) and a 2004 follow-up study (Sheehan et al. 2004). A total of four test sections over both studies (three during the original study and one during the later) were constructed, instrumented, and load tested to measure stresses and strains due to static loads and temperature differentials. Field measurements were used to develop correction factors for theoretical pavement response prediction equations. The main purpose of using calibration factors was to adjust the theoretical stresses and strains to account for the partial bonding at the concrete overlay and asphalt interface.

The original design method based on the 1998 study recommended a minimum subgrade support (k-value) of 150 psi/in. and a minimum asphalt layer thickness of 5 in. The design method was revised because of the 2004 study, including revision of the calibration factors and elimination of the minimum subgrade support and asphalt thickness requirements. In addition, because of these research studies and the historical performance of concrete overlays, CDOT now uses the following typical design features: 6 ft joint spacing, tied concrete shoulders and longitudinal joints, and milling and cleaning for surface preparation.

The CDOT method consists of an iterative design process where the designer evaluates the following inputs:

- Proposed overlay thickness and joint spacing.
- Traffic (ESALs).
- Concrete overlay:
    - Flexural strength, modulus of elasticity, and Poisson's ratio.
- Existing asphalt pavement:
    - Thickness, modulus of elasticity, Poisson's ratio, and amount of asphalt fatigue.
- Subgrade/subbase stiffness (k-value).
- Temperature gradient.

CDOT developed an in-house spreadsheet to implement this procedure. Input variables that have a high to moderate impact on the overlay thickness design include traffic, existing asphalt and proposed overlay modulus of elasticity, k-value, and asphalt layer thickness. Although this procedure was originally developed and calibrated for Colorado, engineers can use this procedure, keeping in mind that it has not been calibrated for other climate zones.

2.5. FHWA Pooled Fund TPF-5(165)

FHWA Pooled Fund project TPF-5(165), Development of a Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements, is currently wrapping up and includes six participating States: Minnesota, Missouri, Mississippi, Pennsylvania, Texas, and New York (http://www.pooledfund.org). Led by Mn/DOT, the purpose of the project is to provide tools that can be used to improve upon current design methods for concrete overlays of asphalt pavements.

This procedure takes advantage of the fact that a substantial number of thin bonded overlays have been in service for an extended period of time and provides six primary enhancements to current methodologies, such as the ACPA BCOA and CDOT methods:

1. The predominant failure modes are redefined.
2. The variability of the asphalt layer stiffness with temperature is considered.
3. The equivalent temperature gradient is defined based on local conditions. (The work performed regarding this enhancement has been recently adopted in the current version of the ACPA BCOA design procedure as well.).
4. The prediction models are calibrated with actual performance data.
5. The effects of fiber on the performance of the overlay are more accurately quantified.
6. The effects of debonding are considered.

Enhancements (1) thru (4) have been incorporated into the current version of the procedure (Vandenbossche et al. 2012).

The work under this effort began with a review of the performance data from bonded overlays representing projects in 11 different States that are towards the end of their intended service life (Barman et al. 2010). The failure mechanisms traditionally assumed for thin and ultrathin bonded overlays were not necessarily reflected in the observed performance. The first observation made was that the actual failure modes of these overlays are dictated by slab size rather than overlay thickness, as had been traditionally assumed. For smaller slabs (e.g., less than 4 ft joint spacings), the longitudinal joint lies within the vicinity of the wheelpath, which results in corner cracking. The wheelpath for larger slabs (e.g., 6 ft by 6 ft slabs), falls in the central portion of the slab. Cracks then initiate at the transverse joint and propagate mainly along the wheelpath to form longitudinal cracks but may occasionally turn and propagate towards the lane/shoulder joint to form diagonal cracks. This design procedure acknowledges these failure modes observed in the field. The procedure incorporates the equations from the ACPA procedure to calculate the stress used to estimate the design life when the panels are less than 4.5 ft in size, and the stress prediction equations from the CDOT procedure are used when the slabs are greater than this size. As described above, the ACPA procedure designs against a corner crack failure, and the CDOT procedure designs against a transverse crack. It should be noted that an analysis was performed using the finite element method to verify that the stress predicted when loading adjacent to the lane/shoulder joint at mid-slab (edge support assumed) was comparable to the stress predicted when the load is applied adjacent to the transverse joint at mid-slab. In a subsequent release, the design procedure will be updated with a stress prediction equation that considers the tensile stress generated by a load placed at the transverse joint at mid-slab.

The asphalt modulus is established internally within the design procedure by first estimating the original modulus and then applying correction factors for the irreversible effects of fatigue and aging of the binder. When establishing the original modulus of the asphalt immediately after paving, a binder is selected based on the geographical location, which is used along with the Witzcak equation. The magnitude of stiffness reduction is defined according to the amount of fatigue cracking observed in the asphalt pavement prior to the placement of the overlay.

The asphalt modulus changes with seasonal and daily temperature variations; however, the thin BCOA design procedures traditionally assume a constant effective asphalt modulus. This assumption predicts a uniform fatigue consumption throughout the year without recognizing an actual increase in fatigue consumption during the summer months and a decrease in fatigue during the winter months. In the TPF-5(165) design procedure, asphalt modulus adjustment factors are used to account for both monthly and hourly temperature fluctuations (Vandenbossche et al. 2012).

Beta Version 1.2 of this spreadsheet-based design procedure was released in May 2012. Copies of this procedure can be obtained at http://www.engr2.pitt.edu/civil/facstaff/personal/vandenbossche/index.html. Traffic can be characterized either as average daily traffic (ADT) or ESALs. The procedure also considers the effect of fiber reinforcement based on work by Roesler et al. (2008), which considers the residual strength ratio of the fiber-reinforced concrete measured according to ASTM C1609-10. (Further enhancements are underway to quantify the effects of fiber on joint performance, as described above under enhancement (5) of the six major enhancements listed above. The effective temperature gradient is determined internally within the design spreadsheet as a function of the climatic zone where the project is located, the pavement structure, and the failure mode. When the information below has been entered into the design spreadsheet, the necessary overlay design thickness is calculated:

- Traffic.
- Design location:
    - Longitude, latitude, and elevation.
    - Climatic zone.
- Existing hot mix asphalt (HMA) pavement:
    - Remaining asphalt thickness.
    - Approximate percent fatigue cracking.
    - Temperature cracking (yes/no).
- Composite subgrade/subbase k-value.
- Concrete overlay:
    - Strength, modulus, fiber residual strength ratio, and CTE.
- Proposed slab size.

A review of the performance of existing projects indicates that reflective cracking may occur if the existing asphalt layer has transverse cracks. This design process includes a check, based on the work of Vandenbossche and Barman (2010), to determine whether there is the potential for reflective cracking. This check does not affect the design thickness but indicates whether preemptive measures should be taken prior to placing the overlay to prevent reflective cracking into the overlay. A common method used to prevent reflective cracking is to place a debonding material, such pavement reinforcement fabric strips or a geotextile, directly on top of the cracks.

Beta Version 1.2 is currently available and includes enhancements (1) through (4) of the six major enhancements outlined above. The design procedure will be finalized, including the incorporation of enhancements 5 and 6, and available for use by the beginning of 2013.

2.6. Design Methodology Applicability

The preceding sections provided a general overview of four different existing concrete overlay design methodologies. An ongoing effort to develop a new methodology for some concrete overlay designs was also described. Based on the initial review and analysis of these methods, the remainder of this guide will expand on design guidance and examples for using the first three (1993 AASHTO Guide, AASHTO Pavement ME Design Guide, and ACPA BCOA methods). The fourth procedure (CDOT) has been successfully implemented only at a local/regional level. Further refinements, calibration, and validation of the CDOT procedure were provided under FHWA Pooled Fund Study TPF-5(165). It was then incorporated into the TPF-5(165) procedure for overlays with panel sizes greater than 4 x 4 ft. As mentioned in the preceding section, it is anticipated that the TPF-5(165) procedure will be finalized in 2013.

Table 2 summarizes more specific design assumptions, deficiencies, and strengths inherent in the 1993 AASHTO Guide, AASHTO Pavement ME Design Guide, and ACPA BCOA methodologies. Two of the most important aspects in concrete overlay design are (1) how each method handles the bond between the existing pavement and the concrete overlay and (2) whether the method assumes the existing pavement will provide significant structural capacity or, alternatively, contribute to the quality of the pavement foundation. With this type of information, pavement designers are able to make an informed decision about which method to apply when designing a certain type of concrete overlay.

Based on the background information discussed for each method and the details presented in table 2, the following sections discuss the 1993 AASHTO Guide and AASHTO Pavement ME Design Guide design methodologies in greater detail for

- Bonded overlays of concrete pavements,
- Unbonded overlays of concrete pavements and composite pavements, and
- Unbonded overlays of asphalt pavements

and the ACPA BCOA overlay design methodology for

- Bonded overlays of asphalt pavements and
- Bonded overlays of composite pavements.

3. Bonded Concrete Overlay Design

In this section, bonded concrete overlay designs procedures are summarized.

3.1. Bonded Overlays of Concrete Pavements, 1993 AASHTO Guide

Section 5.8 of the 1993 AASHTO Guide addresses the thickness design of bonded overlays over existing concrete pavements. The design process is based in the following equation (see figure 5):

$$D_{ol} = D_f - D_{eff}$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

The first part of the design process involves determining the required thickness for a new pavement (D_f) to carry the predicted future traffic. For this, the rigid pavement design equation or nomograph in figure 3.7 in Part II of the 1993 AASHTO Guide is used. It should be noted that a number of inputs used when determining D_f for a bonded overlay correspond to the existing pavement materials and conditions and not to the proposed overlay. Specifically, the elastic modulus, modulus of rupture, load transfer coefficient, and drainage coefficient are representative of the existing pavement. Table 3 lists the inputs required to determine D_f and the corresponding typical ranges.

The effective slab thickness of the existing pavement (D_{eff}) must then be determined with either the Condition Survey or Remaining Life methods described above in Section 2, Background of Design Methodologies. Table 4 summarizes the Condition Survey procedure to estimate D_{eff} when designing a bonded concrete overlay over an existing concrete pavement.

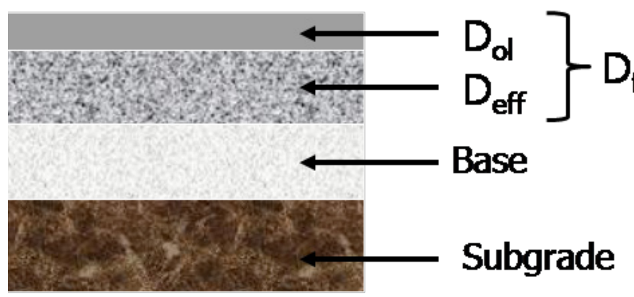

Figure 5. Illustration of Bonded Overlay of Existing Concrete Pavement.

Table 3. 1993 AASHTO Guide Inputs to Determine D_f for Bonded Overlays.

Existing Pavement Inputs	Typical Ranges
Elastic Modulus, E (psi)	3 to 6 million
Modulus of Rupture, S'_c (psi)	600 to 800
Load Transfer Coefficient, J	2.2 to 4.4
Drainage Coefficient, C_d	0.8 to 1.2
General Inputs	**Typical Ranges**
Effective k-value (psi/in.)	50 to 500
Terminal Serviceability, p_t	1.5 to 2.5
Design Serviceability Loss, (triangle)p	1.5 to 2.5
Design Reliability, R (%)	95
Standard Deviation, s_0	0.39
Future Traffic, W_{18} (ESALs)	1 to 100 million

Table 2. Summary of Design Methodology Relevant Assumptions and Items to Note. (After table 8 in the *Guide to Concrete Overlays* [Harrington et al. 2008]).

Overlay Type	Design Method	Design Assumptions, Deficiencies/Strengths, and/or Items to Note
Bonded Overlays of Concrete Pavements	1993 AASHTO Guide	• Assumes complete bond for entire overlay life. • Existing pavement effective structural capacity is based on the Condition Survey or the Remaining Life methods. These two methods have different limitations and may yield inconsistent or unreasonable results. • Pavement designers are familiar with this design process and variables. It has been around for nearly 20 years.
	MEPDG	• Integrates slab geometry, climatic factors, and concrete material and layer properties into thickness design compared to the 1993 AASHTO Guide. • Assumes complete bond for entire overlay life. • This method is still under evaluation, calibration, and implementation by state highway agencies.
Bonded Overlays of Asphalt Pavements	1993 AASHTO Guide	• Not applicable to bonded overlays of asphalt pavements. - Does not account for the bond between the concrete and the asphalt or shorter slab sizes. - Composite k-value is used to account for the existing asphalt, base, and subbase materials. and therefore the existing asphalt contributes to the support layer stiffness and not to the structural slab layer stiffness.
	MEPGDG	• The user inputs the number of months after which the bond between the concrete and asphalt changes from bonded to unbonded. • Similar to the 1993 AASHTO Guide, the MEPDG treats the existing asphalt as a base material that contributes to the concrete layer stiffness. • Not applicable to thinner (two to six inches) bonded overlays of asphalt pavements. The analysis is limited to slab sizes greater than or equal to 10 ft, and this type of concrete overlay typically has shorter slab sizes. • The MEPDG currently refers to the ACPA method for thinner (two to four inches) bonded overlays of asphalt pavements.
	ACPA BCOA	• Evaluates smaller slab sizes, the use of structural fibers in the overlay concrete, and bond plane failure. • Data used for this method's calibration are currently limited to 15 years of overlay performance, and designers need to be careful when extrapolating for longer design life periods. • The current default values in the ACPA web application for the temperature gradient information are representative of the climate conditions in the state of Illinois. Current efforts to define this information for different locations throughout the US are ongoing and are to be included in the web application when available.
Bonded Overlays of Composite Pavements	1993 AASHTO Guide	• Not applicable to bonded overlays of composite pavements. - Does not account for bond and shorter joint spacing, uses a composite k-value, and consequently yields conservative overlay thickness designs.
	MEPDG	• Not originally developed for overlays of composite pavements but can be used correctly by selecting a concrete overlay of asphalt and then inserting a chemically stabilized layer (existing jointed plain concrete pavement [JPCP] or continuously reinforced concrete pavement [CRCP]) under the asphalt layer. • Allows for loss of bond over time, implying that the bond is short term. • Not applicable to thinner (two to six inches) bonded overlays because the analysis is limited to slab sizes greater than or equal to 10 ft and this type of concrete overlay typically involves shorter slab sizes.
	ACPA BCOA	• Addresses bond plane failure, shorter joint spacing, and the use of structural fibers in the overlay concrete. • Not originally developed for overlays of composite pavements but can be used correctly if the equivalent stiffness of the supporting structural layers is input properly. • It has been demonstrated to provide reasonable answers that have proven satisfactory in practice.
Unbonded Overlays (All Types)	1993 AASHTO Guide	• This procedure assumes no friction between the concrete overlay and the existing asphalt pavement or interlayer, uses a composite k-value, and consequently yields conservative thickness designs. • The effective structural capacity of existing concrete and composite pavements is based on the Condition Survey or the Remaining Life methods. These two methods have different limitations and may yield inconsistent or unreasonable results.
	MEPDG	• Integrates slab geometry, climatic factors, and concrete material and support layer properties compared to the 1993 AASHTO Guide. • The asphalt and concrete are treated as unbonded structural layers without any frictional consideration with the concrete overlay. • This method is still under evaluation, calibration, and implementation by state highway agencies.

Bonded overlays should be placed over existing pavements in fair to good condition; therefore, only a limited number of pre-overlay repairs are typically necessary to address any localized distresses. Furthermore, bonded overlays are not recommended when durability problems are present. Therefore, table 4 below indicates that the adjustment factors F_{jc} and F_{dur} for the Condition Survey equation are typically 1.0 or close to 1.0.

Table 5 summarizes the Remaining Life procedure to estimate D_{eff}. As mentioned above, bonded overlays are placed over existing pavements in relatively fair to good condition, and some agencies recommend using a condition factor (CF) equal to 1 for this method (Smith et al. 2002). As discussed above in Section 2, Background of Design Methodologies, the Remaining Life approach does not account for pre-overlay repairs, and thus in some cases it may underestimate D_{eff}.

Note that for bonded overlays, D_{eff} with both procedures described in table 4 and table 5 will likely be close to the original existing slab thickness because the adjustment and condition factors are close to 1.0. D_f and the corresponding inputs for its calculation will likely have the most impact on the overlay thickness design.

3.1.1. Critical Design Variables

Input variables that have a moderate to high impact on bonded concrete overlay thickness design include traffic (W_{18}), load transfer (J), drainage (C_d), and the modulus of rupture (S'_c). The most sensitive input is the expected ESALs, which must be carefully assessed in order to meet the performance expectations for the bonded overlay. The modulus of rupture, load transfer, and drainage coefficients are dependent on the existing pavement condition. Pre-overlay repairs are typically conducted to address major load transfer and/or drainage deficiencies before a bonded overlay is placed to prevent overdesigning the concrete overlay thickness.

Table 4. Summary of the 1993 AASHTO Guide Condition Survey Method and Adjustment Factors.

$D_{eff} = F_{jc}*F_{dur}*F_{fat}*D$, where D = existing slab thickness (in.).	**Joint and cracks adjustment factor**, F_{jc}: Typically 1.0 if all deteriorated cracks and joints are repaired before the overlay. If repairs are not performed, the total number of unrepaired joints and cracks per mile is estimated and Figure 5.12 in Part III of the 1993 AASHTO Guide is used to determine F_{jc}.
	Durability adjustment factor, F_{dur}: 1.0: no signs of durability problems, such as "D" cracking or reactive aggregate distress. 0.96–0.99: durability cracking exists but no spalling. 0.80–0.95: cracking and spalling exists (bonded overlay not ideal solution).
	Fatigue damage adjustment factor, F_{fat}: 0.97–1.00: few transverse cracks/punchouts • JPCP: <5% cracked slabs • CRCP: <4 punchouts per mile 0.94–0.96: significant number of transverse cracks/punchouts • JPCP: 5%–15% cracked slabs • CRCP: 4–12 punchouts per mile 0.90–0.93: large number of transverse cracks/punchouts • JPCP: >15% cracked slabs • CRCP: >12 punchouts per mile

Table 5. Summary of AASHTO Guide Remaining Life Method and Adjustment Factors.

$D_{eff} = CF*D$, where D = existing slab thickness (in.).	**Remaining Life, RL (%):** $RL = 100[1-(N_p/N_{1.5})]$ where N_p=total traffic to date (ESALs) and $N_{1.5}$=total traffic to failure (ESALs). Use Figure 5.2 in Part III of the 1993 AASHTO Guide to determine the CF based on RL.

3.2. Bonded Overlays of Concrete Pavements, AASHTO Pavement ME Design Guide

In order to provide an overview of the AASHTO Pavement ME Design Guide iterative design process, screen captures for the AASHTOWare Pavement ME Design inputs are provided. Recommended modifications to the trial designs are presented by addressing the most sensitive design variables when performance criteria are not met.

To begin a design for a bonded overlay of concrete pavement, the General Information menu is used to select the portland cement concrete (PCC) overlay type and indicate whether it is a bonded PCC overlay over an existing JPCP or CRCP. Additional general information includes the design life (years), the estimated construction dates of the existing pavement and proposed overlay, and when the overlay is expected to be opened to traffic.

3.2.1. Traffic

Traffic inputs for the AASHTOWare Pavement ME Design are based on traffic load spectra, which describe the vehicle class distribution in terms of the number, weight, and geometries of the associated axle loads within each classification. It further characterizes the traffic distribution by season and time of day. Traffic input Levels 1 and 2 are based on automated vehicle classification (AVC) and weigh in-motion (WIM) measurements, which can be either segment-specific or regional average values; Level 3 inputs are based on nationally developed default distributions from the Long-Term Pavement Performance (LTPP) database.

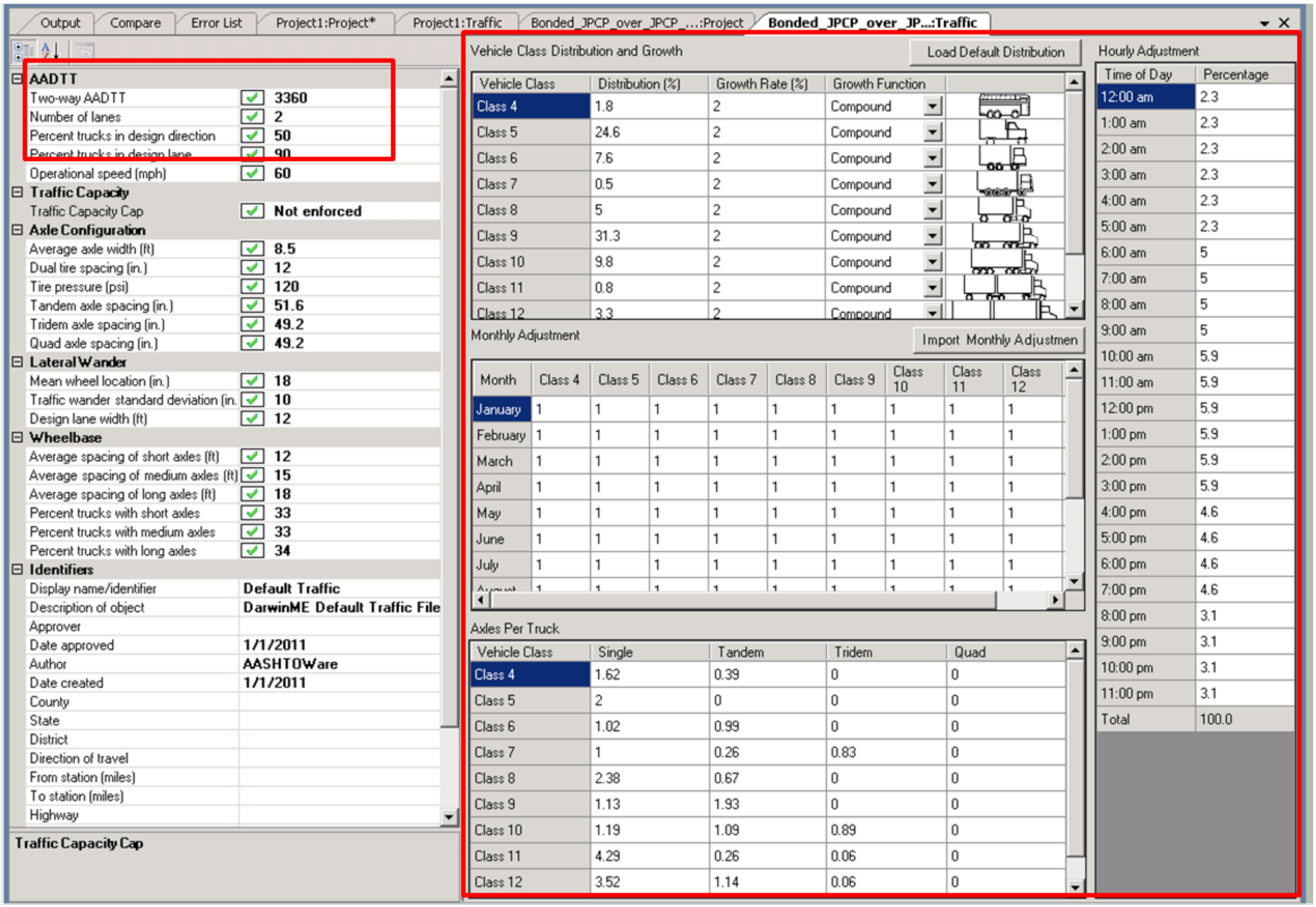

Figure 6. Screen Capture of AASHTOWare Pavement ME Design Traffic Menu.

The main Traffic screen (see figure 6) requires the annual average daily truck traffic (AADTT), the directional distribution factor, and the lane distribution factor. Also on this screen, the traffic adjustment factors are required and include vehicle class distribution and growth, monthly adjustment, axles per truck, and hourly truck distribution factors.

If project-specific traffic adjustment factors information is not available, default values can be used. For example, default vehicle class distribution may be loaded for the different road functional classifications as a default truck traffic classification (TTC) group. Next, the designer enters the growth rate and growth function (linear or compound) for each vehicle class. Other default values in the software assume an equal monthly vehicle distribution, as well as default axles per truck and hourly truck distributions.

Other general traffic inputs on the main Traffic screen (see figure 6) cover items particularly relevant to the analysis of concrete pavements and overlays, such as mean wheel location, traffic wander standard deviation, and axle and wheel geometry. It is important for the designer to review these inputs even if default values are used.

The axle load distribution factors (single, tandem, tridem, and quad) are also traffic inputs. This information is obtained from WIM data, and the AASHTO Pavement ME Design software has been preloaded with default values based on LTPP data. This information is very important because it defines the percentage of axles at each axle weight.

3.2.2. Foundation Support, Pavement Type Design Properties, and Rehabilitation

The next menu in AASHTOWare Pavement ME Design is Foundation Support. In this menu, the user enters the modulus of subgrade reaction (AASHTO Pavement ME Design software requires dynamic k-value) or selects the option to let the program calculate it (based on the pavement structure layers defined later).

The JPCP Design Properties menu is used to enter the joint spacing and dowel inputs that correspond to the existing pavement. The base erodibility index is estimated based on the base material description. For the existing PCC-base interface, the "No friction" option is selected when the base consists of granular materials or subgrade to indicate that the existing PCC slab and the base are unbonded. Other base types, such as asphalt or cement-treated bases, are more likely to be bonded to the existing concrete slab, and the user selects the "Full friction" option and provides the estimated number of months that the bond will last. For CRCP overlays, steel reinforcement for the proposed overlay is input instead of joint information.

Next, the Rehabilitation menu is used when the existing pavement is repaired before the rehabilitation/restoration activities. In most cases, the existing pavement is in good to fair condition before applying a bonded overlay, and no repair information is entered in this menu.

3.2.3. Climate

AASHTOWare Pavement ME Design allows users to load climatic information (air temperature, solar radiation, wind, humidity) from an extensive database of cities across the U.S. and allows data to be interpolated from weather stations near a specific project. The designer also enters the seasonal or constant water table depth for the project location. Climatic factors in the AASHTO Pavement ME Design Guide have been shown to have a significant impact on concrete pavement and overlay performance.

3.2.4. Pavement Structure

The Pavement Structure menu (figure 7) is used to define the pavement system layers and each layer's material properties. Only the proposed concrete overlay and significant structural layers will be discussed. The overlay and existing concrete pavement layer are both defined in terms of general (PCC), thermal, mix, shrinkage, and strength properties. General properties for these two layers include thickness, unit weight, and Poisson's ratio.

Thermal properties include CTE, thermal conductivity, and heat capacity. The default values in AASHTOWare Pavement ME Design are recommended for all of these properties except for CTE. The AASHTO Pavement ME Design Guide considers CTE a critical design variable for bonded overlays of existing concrete pavements. Determining this value in the laboratory for both the overlay and the existing concrete pavement is

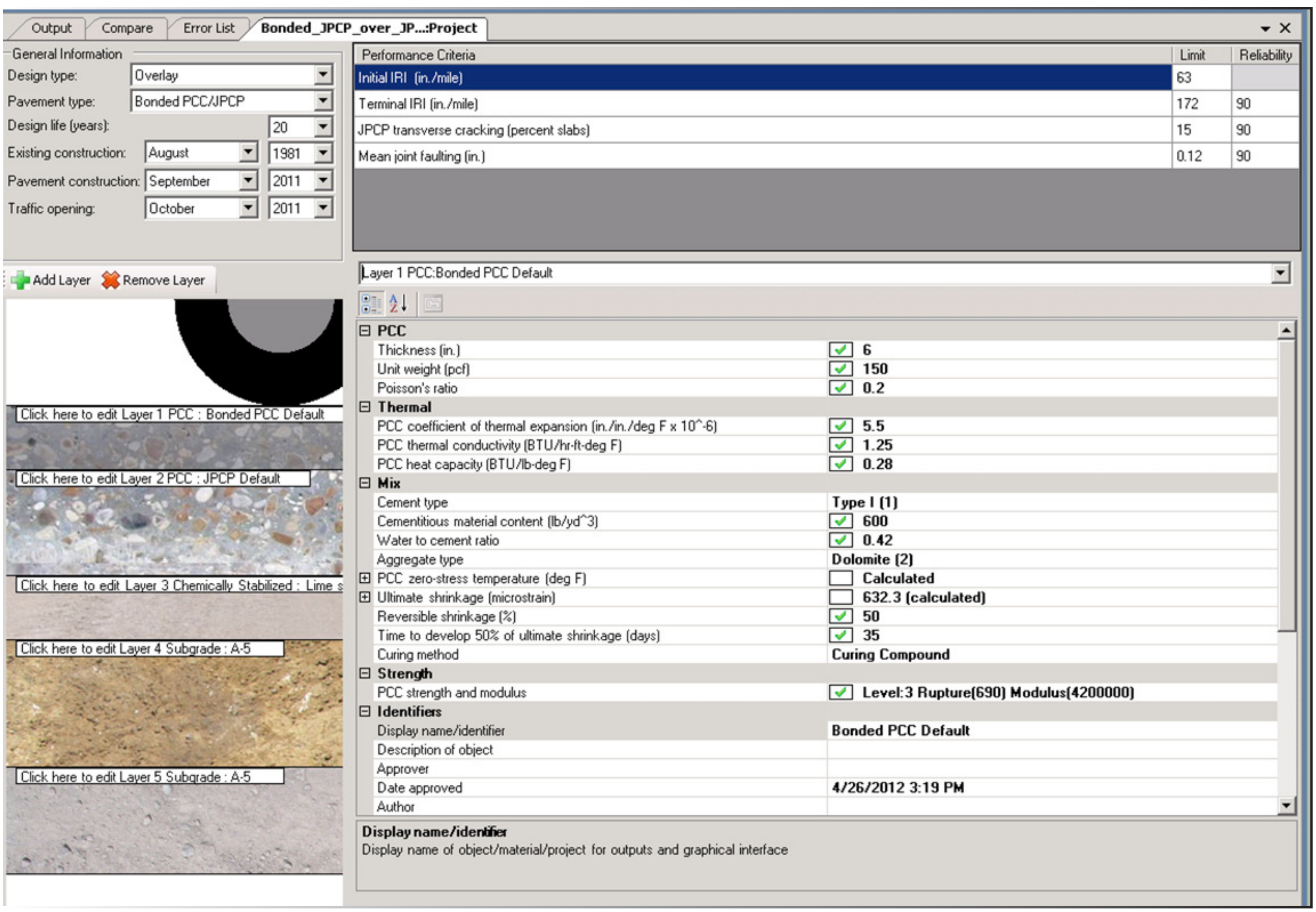

Figure 7. Screen Capture of AASHTOWare Pavement ME Design Pavement Structure/Layers Menu.

recommended. CTE may also be determined using the CTE-weighted average of the concrete mixture components. (Typical values are presented in table 6.)

AASHTO TP 60, Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete, has been used for a number of years to determine CTE. The CTE values presented in table 6 are representative of this standard, and the current AASHTO Pavement ME Design software is calibrated using CTE values obtained through this method. However, issues with the equipment calibration procedure in AASHTO TP 60 were recently identified, and a new procedure, AASHTO T 336, was developed to rectify those problems (Tanesi et al. 2010). Note that the CTE values obtained with these two procedures may vary significantly, and it is expected that the models in future versions of the AASHTO Pavement ME Design software will be recalibrated to account for this difference. The examples in this guide are presented using the current AASHTOWare Pavement ME Design version, which contains the models based on data tested following AASHTO TP 60.

The following set of inputs is for mix properties, which are project specific and should be obtained from the concrete mix design and specifications. These include cement type and content, water/cement ratio, and aggregate type.

Next, the PCC zero-stress temperature can be input directly to the AASHTOWare Pavement ME Design or estimated by the program internally based on the construction month entered in the General Information menu. Section 3.4.3.7 in the M-E PDG manual (NCHRP 2004) explains that this estimate is based on daytime construction with curing compound and does not account for the effect of mineral, chemical, and other admixtures. The PCC zero-stress temperature represents the temperature at which the concrete hardens sufficiently to develop tensile stresses. At this point, the cracks in the CRCP open when the concrete temperature drops below this value. Paving during the summer months results in high zero-stress temperatures and wider crack openings when the temperature drops.

Table 6. Typical CTE Ranges for Concrete and Constituents.

Material Type		CTE, a (10-6/°F)
Aggregate	Granite	4-5
	Basalt	3.3-4.4
	Limestone	3.3
	Dolomite	4-5.5
	Sandstone	6.1-6.7
	Quartzite	6.1-7.2
	Marble	2.2-4
Cement paste		10-11
Concrete		4.1-7.3 (typical value 5.5)

The strength properties are critical design variables in the AASHTO Pavement ME Design Guide. These properties include modulus of elasticity and modulus of rupture for JPCP and CRCP overlay design. As with the 1993 AASHTO Guide method, the compressive strength can be used to estimate the strength properties of the existing concrete pavement and of the new concrete overlay if the modulus of rupture is not directly measured. In addition, deflection testing may be used to estimate the elastic modulus of the existing pavement. Note that sampling and deflection testing of existing concrete pavements is typically conducted on areas that are not severely deteriorated; therefore, the estimated modulus of elasticity needs to be adjusted to represent the overall condition of the section under evaluation. Titus-Glover and Stanley (2008) present guidance on how to select an appropriate modulus of elasticity for existing JPCP.

3.2.5. Critical Design Variables

Chapter 7 of Part 3 of the M-E PDG manual (NCHRP 2004), PCC Rehabilitation Design of Existing Pavements, describes the critical design variables that affect each type of concrete overlay. This chapter also presents strategies to modify trial designs that do not meet the established performance criteria, such as the criteria for cracking and faulting (and consequently IRI). For example, for bonded overlays of concrete pavements, the designer should consider increasing the overlay thickness and/or adding a concrete shoulder.

Recommendations for bonded overlays of CRCP designs not meeting the performance criteria include increasing the overlay thickness, changing the steel content, and/or adding a tied concrete shoulder. With the AASHTO Pavement ME Design procedure, minimum combined thicknesses for the existing concrete pavement and concrete overlay of 6 and 7 in. are used for JPCP and CRCP analysis, respectively

3.3. Bonded Overlays of HMA and Composite Pavements, ACPA Method

Bonded overlays of asphalt pavements were previously referred to as ultrathin whitetopping (UTW) for thicknesses between 2 and 4 in. or thin whitetopping (TWT) for thicknesses between 4 and 6 in. Smaller slab sizes are used for this type of overlay—typically between 4 and 6 ft, cut both longitudinally and transversely, as shown in figure 8.

In addition to the Guide to Concrete Overlays (2008), NCHRP Synthesis 338 documents the state of the practice for designing and applying these overlays. The ACPA design procedure (ACPA 1998) and its latest improvements (Riley 2006, Roesler et al. 2008, and Vandenbossche et al. 2012) for

Figure 8. Bonded Concrete Overlay of Asphalt Pavement.

these types of overlays were described in Section 2, Background of Design Methodologies.

As mentioned above, the latest improvements that Riley (2006), Roesler et al. (2008), and Vandenbossche et al. (2012) made to the ACPA design methodology were incorporated into the BCOA thickness design web application (see figure 9), which is available at http://apps.acpa.org/apps/bcoa.aspx. The current design process calculates the proposed overlay slab thickness based on the slab geometry, traffic, layer thickness, and material property inputs.

As shown in figure 9, the ACPA BCOA web tool begins with the General Design Details, specifically traffic, which includes the design lane ESALs that may be directly input or estimated using an embedded ESAL calculator. Riley (2006) notes that BCOA field performance data are currently up to 15 years old, and thus designers should limit their pavement design lives to a maximum of 20 years. Next, the failure criteria are entered in terms of maximum percentage of cracked slabs and reliability. Lastly, the nearest city to the BCOA design is selected so that the program can calculate internally the appropriate effective temperature gradient.

The next section in the BCOA application is Existing Pavement Structure Details, which includes the thickness of the existing asphalt layer after surface preparation and the existing layer's corresponding effective elastic modulus. Another input is the composite modulus of subgrade reaction (k-value) for the existing subgrade combined with the existing base (described as the k-value at the bottom of the asphalt layer). Note that this method was not originally developed for overlays of composite pavements but can be used if the equivalent stiffness of the supporting structural layers is input properly; the existing concrete layer does have a significant effect on overlay thickness.

The Concrete Material Details are input to describe the properties of the proposed overlay. If no project-specific information is available, designers may base their inputs on the typical values that the local agency uses for the average 28-day third-point flexural strength, elastic modulus, and CTE. The flexural strength input for this method is the average value and not the minimum. In addition, the use of structural fibers and the residual strength ratio based on ASTM C1609-10 is input in this section. Note that some agencies specify macrofibers for slab thicknesses less than 4 in. for increasing serviceability and the structural capacity of the overlay.

The last section, Concrete Overlay Details, includes the proposed joint spacing for the overlay and the type of surface preparation that will be performed. Shorter joint spacings (both transverse and longitudinal) are typically used for bonded overlays over asphalt pavements, such as 4 ft by 4 ft or 6 ft by 6 ft slabs for a 12 ft wide lane. At this point, the BCOA calculates a slab thickness based on the inputs provided. The designer should modify the design inputs accordingly until a satisfactory design is achieved.

Note that the web application does not allow thicknesses thinner than 3 in. and thicker than 6 in., and if the BCOA application calculates a thickness outside this range it provides warnings to indicate that the trial design needs to be modified or that a bonded overlay of asphalt pavement may not be the appropriate solution. Also note that the CDOT and TPF-5(165) procedures described above in Sections 2.4 and 2.5 should be considered when BCOA designs are approaching 6 in. in thickness and 6 ft slabs.

3.3.1. Critical Design Variables

Riley (2006b) and Roesler et al. (2008) list several critical design variables, such as existing asphalt thickness and stiffness, concrete overlay flexural strength, slab size, effective temperature gradient, and use of structural fibers. Furthermore, care is required when selecting the concrete mixture design to avoid excessive concrete drying shrinkage. While proper curing can reduce concrete early-age shrinkage, selection of the concrete mixture proportions will still significantly affect this property. Adequate surface preparation is also important. Excess shrinkage and/or improper surface preparation can lead to debonding at the concrete-asphalt interface.

4. Unbonded Concrete Overlay Design

In this section, the procedures outlined for each of the three design methodologies with respect to unbonded concrete overlays are described.

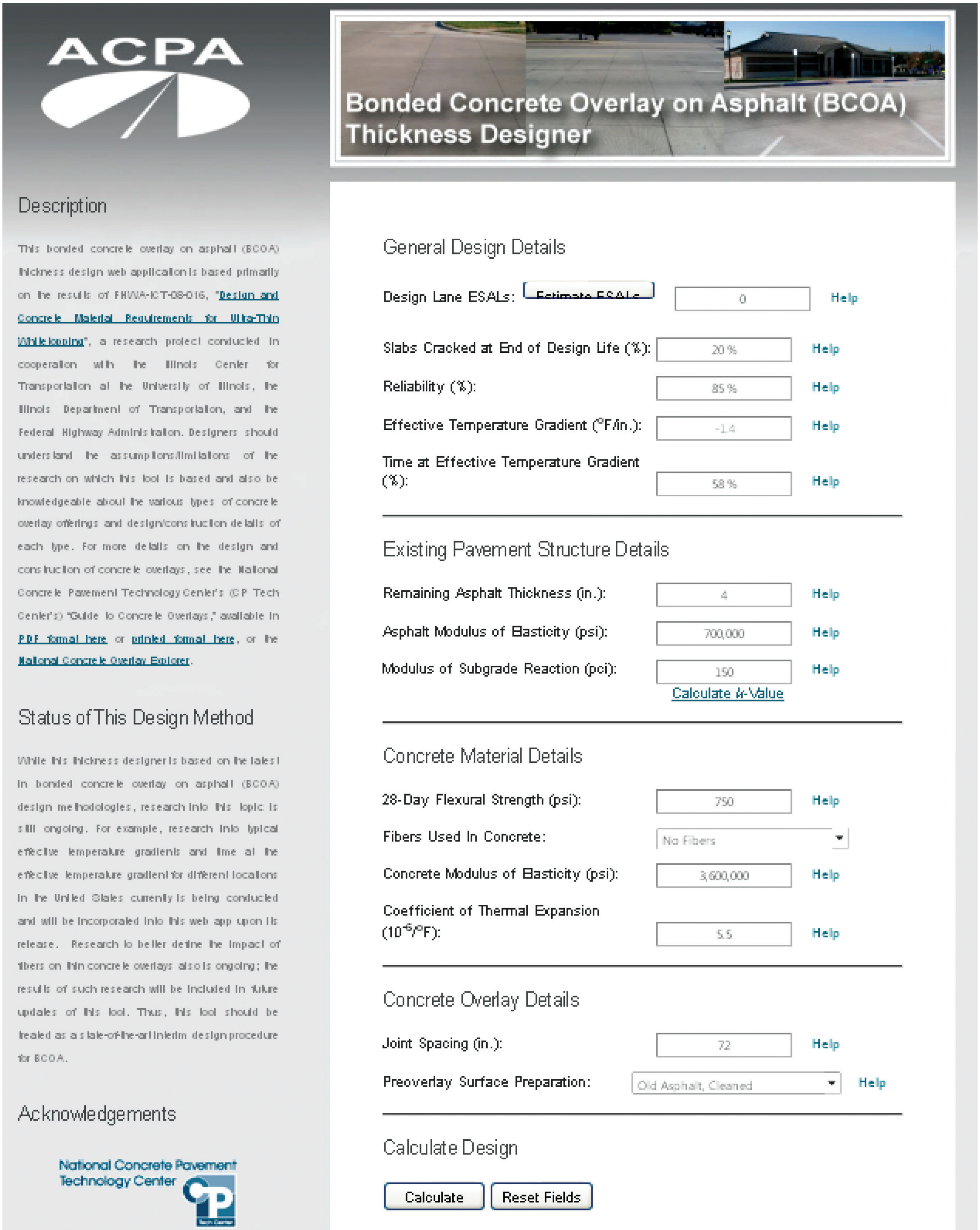

Figure 9. ACPA BCOA Thickness Design Web-based Application.

4.1. Unbonded Overlays of Concrete and Composite Pavements, 1993 AASHTO Guide

Section 5.9 of the 1993 AASHTO Guide covers the design of unbonded overlays of existing concrete and composite pavements. The design process is based on the following equation (see figure 10):

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})}$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

The design of unbonded overlays is similar to that of bonded overlays in terms of determining D_f. The rigid pavement design equation or nomograph in figure 3.7 in Part II of the 1993 AASHTO Guide is used, but the values for the slab elastic modulus, modulus of rupture, load transfer, and drainage coefficients are for the concrete overlay and not the existing concrete pavement. The inputs and typical ranges shown in table 3 also apply to calculating D_f for unbonded overlays.

D_{eff} is determined using the Condition Survey or Remaining Life procedures. Table 7 summarizes the Condition Survey method for unbonded overlays. The Remaining Life method follows the steps described for bonded overlays in table 5, with two exceptions: (1) D cannot exceed 10 in. (even if the existing pavement is thicker) and (2) the Remaining Life method is not applicable to composite pavements.

Smith et al. (2002) and ACI Committee 325 (2006) have discussed the following major limitations on unbonded overlay designs that apply to the 1993 AASHTO Guide:

- Lack of consideration of the structural contribution of the interlayer and its interaction in terms of friction or bonding with the overlay and existing pavement.
- Overestimation of the existing pavement effective thickness when the existing slab is relatively thick.
- Lack of consideration of curling and joint spacing in the concrete overlay.

4.1.1. Separator Layer

It is common to use an asphalt interlayer between existing concrete slabs and new concrete overlays. The 1993 AASHTO Guide does not account for the interlayer's structural contribution, and therefore only general recommendations are given, such as "experience has shown that a 1 to 2 in. asphalt interlayer works well ." In addition, experience has shown that the drainage properties of the separator layer are a critical factor for overlay performance. In some cases, States specify an erosion- and moisture-resistant dense-graded mixture, while other States specify a well-drained open-graded mixture.

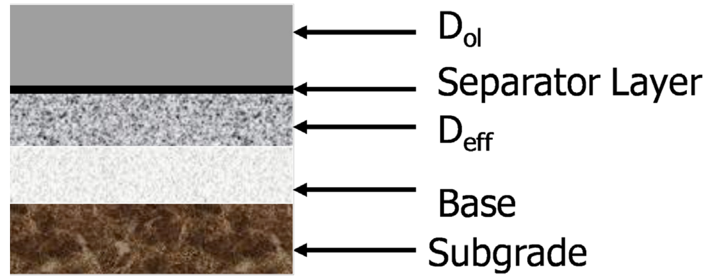

Figure 10. Illustration of Bonded Overlay of Existing Concrete Pavement.

Table 7. Summary of the 1993 AASHTO Guide Condition Survey Method for Unbonded Overlays.

$D_{eff} = F_{jcu}$*D where, D=existing slab thickness (in.) For composite pavements, neglect the asphalt thickness	The joints and cracks adjustment factor for unbonded overlays (F_{jcu}) is used to account for the deteriorated cracks and joints that are not repaired before the unbonded overlay. Figure 5.13 in Part III of the 1993 AASHTO Guide is used to determine F_{jcu}, which ranges from 0.9 to 1 and is based on the total number of unrepaired deteriorated joints/cracks and other discontinuities per mile. When a thick asphalt interlayer is applied (greater than 1 inch), it is likely to eliminate reflection cracking problems, so an F_{jcu} value of 1 is used.

Designers are to follow local guidelines to ensure the asphalt interlayer works well with other drainage features used locally.

For unbonded overlays of existing composite pavements, the existing asphalt to remain in place needs to be assessed to ensure its adequacy in terms of structure and drainage properties.

In some cases, an alternative to an asphalt interlayer is a nonwoven geotextile interlayer. According to German design practices and expertise, it is recommend that the design thickness calculated using the 1993 AASHTO Guide be increased by 0.5 in. when a nonwoven geotextile interlayer is used in lieu of asphalt. The structural condition of the existing concrete pavement must be carefully assessed before selecting a geotextile instead of an asphalt interlayer.

4.1.2. Critical Design Variables

Critical design variables that have a moderate to high impact on the thickness design of unbonded overlays over concrete and composite pavements include traffic (W_{18}), load transfer (J), drainage coefficient (C_d), modulus of rupture (S'_c), effective k-value, and change in serviceability (ΔPSI).

In the 1993 AASHTO Guide, the unbonded overlay is designed using the same structural design procedure as that used for a new pavement. For designs based on the 1993 AASHTO Guide, dowel bars at the joints significantly affect the overlay thickness by changing the load transfer coefficient (J) from 4.4 to 3.2.

Figure 11. Construction of Unbonded Overlay with Nonwoven Geotextile Interlayer.

Drainage improvements and an accurate knowledge of the mean concrete strength also impact the input drainage coefficient and the modulus of rupture, respectively. Traffic and support conditions are sensitive design inputs but do not vary for a given project.

4.2. Unbonded Overlays of Concrete and Composite Pavements, AASHTO Pavement ME Design Guide

The design process for unbonded overlays of concrete or composite pavements using AASHTOWare Pavement ME Design follows the general steps described above for bonded overlays. Under the General Information menu, the type of unbonded overlay is selected, such as JPCP over JPCP, JPCP over CRCP, CRCP over JPCP, or CRCP over CRCP. The Traffic and Climate inputs are the same as those used in the design of bonded overlays. The Pavement Structure inputs represent the main differences.

4.2.1. Pavement Type Design Properties

The Design Properties menu includes joint design information for JPCP. The joint spacing for unbonded overlays is typically recommended to be shorter than the spacing for new pavements, and the joints in the new overlay do not need to match the existing pavement joints/cracks. The AASHTO Pavement ME Design Guide (see table on page 3.7.17 of the M-E PDG manual [NCHRP 2004]) recommends offsetting the overlay joints a minimum of 3 ft from the existing pavement joints to improve load transfer, as shown in figure 12. However, many States do not intentionally match or mismatch joints for unbonded overlays and have not experienced any adverse effects (Harrington et al. 2008). Dowels may not be required, but, if needed to address faulting, the spacing and diameter are determined following the same guidelines as for new JPCP.

For CRCP, the Design Properties menu includes the steel reinforcement information instead of joint design information, including percent of steel, bar diameter, and steel depth. Longitudinal steel reinforcement for unbonded CRCP overlays is designed following the same guidelines as for new CRCP. The

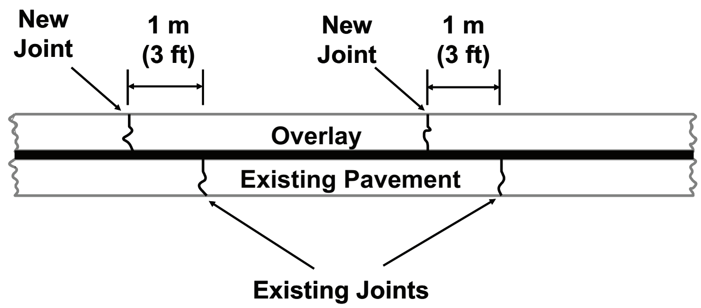

Figure 12. Unbonded Overlays with Mismatching Joints (ACPA 1990).

Figure 13. Asphalt Separation Layer.

M-E PDG manual (NCHRP 2004) cites typical values of 0.6 percent to 0.75 percent of steel, a bar diameter of 0.625 to 0.75 in., and steel depths of 3.5 in. to mid-depth.

In the same Design Properties menu, the base properties information includes the erodibility index. For both JPCP and CRCP unbonded overlays, the asphalt separation layer (shown in figure 13) is used, and if the asphalt interlayer is of good quality an erodibility index of 1 (extremely resistant) is recommended. For JPCP unbonded overlays, the PCC slab-base interface is automatically set as “zero friction”/no bond. For CRCP unbonded overlays, a base-slab friction coefficient of 7.5 is recommended when an asphalt separation layer is used, but this value may be changed if necessary.

4.2.2. Pavement Structure

The Pavement Structure menu is used for defining the proposed overlay in terms of general (PCC), thermal, mix, and strength properties, which are estimated in a fashion similar to that for bonded overlays. Also in this menu, the asphalt interlayer, in addition to the existing JPCP, requires material property inputs.

When designing an unbonded overlay of an existing concrete pavement with a nonwoven geotextile interlayer, a modified approach using the AASHTO Pavement ME Design Guide must be adopted. As discussed above, an asphalt interlayer is identified as its own layer under the Pavement Structure menu. There is no option, however, for choosing and characterizing a nonwoven geotextile layer. Instead, it is recommended that an analysis using a 2 inch asphalt interlayer be performed. Once an adequate design has been calculated, the resulting overlay thickness should be increased by 0.5 in., according to German design practices and expertise (Hall et al. 2007). The purpose of the increased thickness is to accommodate increased stresses because of the more compliant interlayer.

4.2.3. Critical Design Variables

To address trial designs for JPCP unbonded overlays that do not meet the performance criteria for faulting and cracking (and consequently smoothness), the designer should consider increasing the overlay thickness, decreasing the joint spacing, using dowel bars (or increasing their diameter), using a widened lane, or adding tied concrete shoulders. Recommendations for unbonded CRCP overlay designs that do not meet performance criteria include increasing the overlay thickness, increasing the percent of longitudinal steel reinforcement, and adding a concrete shoulder.

4.3. Unbonded Concrete Overlays of Asphalt Pavements, 1993 AASHTO Guide

Section 5.10 of the 1993 AASHTO Guide covers the design of unbonded overlays of existing asphalt pavements. This alternative is most cost-effective when the existing flexible pavement is severely deteriorated. For thickness design purposes, the existing asphalt pavement is treated as the base and the concrete overlay is designed as a new concrete pavement based on the future traffic to be carried. The design process is based on the following equation (see figure 14):

$$D_{ol} = D_f$$

Where, D_{ol} = required concrete overlay thickness (in.), and D_f = slab thickness required to carry the future traffic (in.).

The design process to determine the overlay thickness (D_{ol}) involves the same steps and inputs described above for unbonded overlays of concrete and composite pavements.

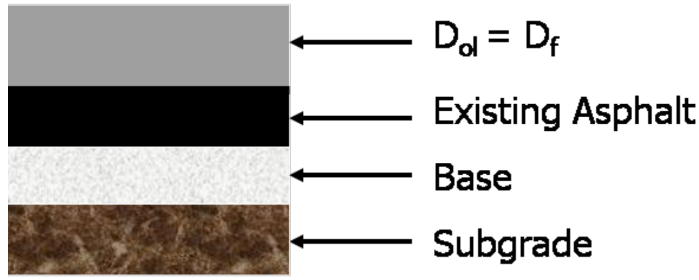

Figure 14. Illustration of Unbonded Overlay of Existing Asphalt Pavement.

4.3.1. Critical Design Variables

Critical design variables that have a moderate to high impact on the thickness design of unbonded overlays over asphalt pavements include traffic (W_{18}), load transfer (J), drainage coefficient (C_d), modulus of rupture (S'_c), and composite k-value. These sensitivities are similar to those for unbonded overlays of concrete pavements.

4.4. Unbonded Concrete Overlays of Asphalt Pavements, AASHTO Pavement ME Design Guide

The AASHTO Pavement ME Design process for unbonded overlays of asphalt pavements also follows guidelines similar to those for designing new concrete pavements, where the existing asphalt pavement is treated as the base. A key input for this procedure, under the Design Properties menu, is the "PCC-base contact friction" for JPCP and the "Base/slab friction coefficient" for CRCP. An unbonded condition between the overlay and the existing pavement is typically assumed. Therefore, the "PCC-base contact friction" value is set to "no friction" for JPCP overlays, and the "Base/slab friction coefficient" value is set to 7.5 as the mean default for CRCP or asphalt. The selection of this concrete-asphalt interface condition can have a significant impact on the overlay thickness design.

4.4.1. Critical Design Variables

To address trial designs for JPCP unbonded overlays of asphalt pavements that do not meet the performance criteria for faulting and cracking (and consequently IRI), the designer should consider decreasing the joint spacing, inserting dowel bars (or increasing their diameter), widening the slab, or adding a tied concrete shoulder. Recommendations for a CRCP unbonded overlay of asphalt pavement designs not meeting the performance criteria include increasing the overlay thickness, increasing the percent of longitudinal steel reinforcement, or adding tied concrete shoulders.

5. Overlay Design Examples

In this section, step-by-step examples are presented to demonstrate the general approach to designing concrete overlays using the methodologies described above. In developing these examples, interviews were conducted with various State DOT pavement design engineers who have different levels of experience with concrete overlays. The intent of the interviews was to learn about the general (typical) practices for pavement design so that the examples provided herein would be of most value. The examples provided herein are based on typical case studies provided by States that are actively designing and constructing concrete overlays. As a result, they represent some of the more typical scenarios that might be encountered in terms of concrete overlay candidate projects.

Each example is organized as follows:

1. Scenario/Project description:
   - Roadway typical section.
   - Pavement cross-section.
   - Applicable design inputs.
   - Design steps.
2. Effect of changing critical design variables.
3. Summary of results.

Table 8 presents a summary of the design examples according to overlay type, existing pavement type, design method, and description of impact when changing specific design variables.

5.1. Bonded Overlay over Existing Concrete Pavement

5.1.1. Scenario

A JPCP along a Rural Interstate built in 1981 is scheduled for rehabilitation. The existing pavement is 8 in. thick over 6 in. of lime-stabilized subgrade. Lanes are 12 ft wide, with 15 ft transverse joint spacing and 10 ft wide concrete shoulders. A

Table 8. Summary of Design Examples.

Section	Concrete Overlay Type	Existing Pavement	Design Method	Changing Design Variables
5.1	Bonded over Concrete	JPCP	1993 AASHTO Guide	Design life/traffic Concrete strength
			AASHTO Pavement ME Design Guide	CTE – overlay and existing pavement CTE – overlay
5.2	Bonded over Asphalt	Asphalt	ACPA BCOA	Asphalt thickness
				Temperature differentials
5.3	Bonded over Composite	Asphalt	ACPA BCOA	Slab size: Thickness and joint spacing
				Structural Fibers
5.4	Unbonded over Concrete	JPCP	1993 AASHTO Guide	Load transfer: Dowels and tied concrete shoulders Design serviceability loss
			AASHTO Pavement ME Design Guide	Load transfer: Dowels
5.5	Unbonded over Asphalt	Asphalt	1993 AASHTO Guide	Design life/traffic Load transfer: Tied concrete shoulders
			AASHTO Pavement ME Design Guide	Design life/traffic Load transfer: Tied concrete shoulders
5.6	Unbonded over Composite	CRCP	1993 AASHTO Guide	Design life/traffic k-value
			AASHTO Pavement ME Design Guide	Design life/traffic PCC zero-stress temperature
5.7	Unbonded over Composite	JPCP	1993 AASHTO Guide	Load transfer: Asphalt shoulders Modulus of rupture
			AASHTO Pavement ME Design Guide	Widened slab and asphalt shoulders Joint spacing

detailed pavement evaluation revealed that the existing concrete is in relatively good condition and, as a result, a bonded concrete overlay is being considered for rehabilitation purposes. In order to design the bonded overlay effectively, the following design information has been gathered:

- Historical Records
  - Pavement age: 30 years.
  - 1.25 in. dowel bars at transverse joints, 12 in. spacing.
  - Estimated cumulative ESALs to date: 10 million.
  - Existing pavement originally designed for 25 million ESALs to failure (terminal PSI = 1.5).
  - Soil survey indicates that subgrade materials consist mainly of silty soils (A-5).
- Deflection Testing Results (Falling Weight Deflectometer [FWD])
  - Effective dynamic k-value (psi/in.): 550.
  - Back-calculated E (psi) for concrete, base, and subgrade: 4,700,000, 58,000, and 20,000, respectively (see figure 15). Note that for the subgrade resilient modulus (Mr) input to AASHTOWare Pavement ME Design, the backcalculated value is adjusted to represent laboratory conditions. In this case, 0.35*backcalculated Mr (psi): 7,000.
  - FWD testing for joint load transfer at representative joints averaged a load transfer efficiency (LTE) of 98%.
- Coring and Materials Testing Results (Existing Concrete)
  - S'_c, concrete modulus of rupture (psi): 740 (correlation with compressive strength tests).
  - CTE (10^{-6}/°F): 4.5.
- Distress Survey Results
  - Estimated number of unrepaired spalling areas and deteriorated transverse joints and cracks: 20 per mile.
  - No signs of concrete durability problems, such as "D" cracking or reactive aggregate distresses.
  - Very few, < 2%, slabs are cracked.

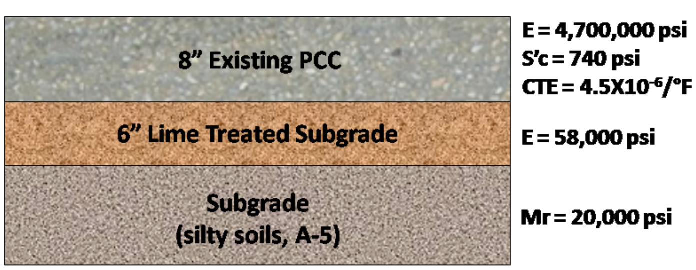

Figure 15. Summary of Existing Pavement Cross-Section.

Traffic

- Future ESALs (20-year design life): 24.78 million.
- Initial two-way AADT: 16,800; Trucks: 20%; Growth rate: 2% (compound).
- Existing roadway: 4 lanes (2 lanes each way).
- Directional distribution: 50%; Design lane distribution factor: 90%.

Climate

- Location: near Fort Worth, Texas.
- Annual average water table depth: 10 ft.

Proposed Overlay

- E (psi) for concrete: 4,800,000.
- 28-day flexural strength (psi): 680.
- CTE (10^{-6}/°F): 4.5.

The following sections illustrate how to perform the overlay design for this example using both the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide.

5.1.2. 1993 AASHTO Guide

The design of bonded overlays over existing concrete pavements using the 1993 AASHTO Guide is based on the following equation:

$$D_{ol} = D_f - D_{eff}$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

Step 1. Determine D_f

Determine D_f using the rigid pavement design equation or nomograph in figure 3.7 in Part II (pg. II-45) of the 1993 AASHTO Guide. Table 9 summarizes the inputs used to determine D_f. Note that for the design of bonded overlays over concrete pavements, the elastic modulus, modulus of rupture, load transfer coefficient, and drainage coefficient correspond to the existing concrete pavement. Use of the nomograph yields a required slab thickness (D_f) of 11.3 in.

Step 2. Determine D_{eff}

Determine D_{eff} using either the Condition Survey (see table 4) or Remaining Life method (See table 5) as described in Section 3.1.

Condition Survey Method

Based on the distress survey results, determine the adjustment factors to use the following equation:

$$D_{eff} = F_{jc} * F_{dur} * F_{fat} * D$$

Table 9. Summary of Design Inputs for D_f.

Input (Units)	Calculations/Estimates	Value
Effective static k-value, psi/in.	Effective dynamic k-value (from deflection testing) / 2 = 1000 / 2	275
E, Concrete elastic modulus, psi	For proposed overlay: estimated from project mix designs and specifications	4,700,000
S'_c, Concrete modulus of rupture, psi		740
J, Load transfer factor	From deflection testing, LTE: 98%, From Section 5.8 of the 1993 AASHTO Guide: For JPCP and JRCP: LTE >70%: J= 3.2; 50%<LTE<70%: J= 3.5; LTE<50%: J= 4.0	3.2
C_d, Drainage coefficient	Typically 1.0 for poor subdrainage conditions	1.0
Δp, Design serviceability loss	(Initial Serviceability: 4.5) – (Terminal Serviceability: 2.5)	2.0
R, Reliability (%)	Typical value for high-traffic concrete overlay	95
S_o, Standard deviation	Typical value for high-traffic concrete overlay	0.39
W_{18}, Future traffic (ESALs)	ESAL calculations according to local/regional load equivalency factors	24,780,000

Where, D = existing slab thickness (in.), 8 in.

F_{jc} = joint and cracks adjustment factor, 0.94

- Determined using figure 5.12 in Part III of 1993 AASHTO Guide (see figure 16) and the total number of unrepaired spalling areas and deteriorated joints and cracks per mile, which in this case is 20

F_{dur} = durability adjustment factor, 1.0

- Because no signs of durability problems or material-related distresses were identified

F_{fat} = fatigue damage adjustment factor, 0.99

- Because F_{fat} ranges from 0.97 to 1.0, and in this case very few slabs are cracked

The effective thickness of the existing concrete slab calculated with this method is as follows:

$$D_{eff} = F_{jc}*F_{dur}*F_{fat}*D = 0.94*1.0*0.99*8 = 7.44 \text{ in.}$$

Remaining Life Method

Based on past traffic, determine the existing pavement remaining fatigue life using this equation:

$$RL (\%) = 100*[1-(N_p / N_{1.5})]$$

Where, N_p= total traffic to date (ESALs), 10 million, and $N_{1.5}$= total traffic to failure (ESALs), 25 million.

Taking into account these traffic inputs, the remaining life can be calculated as follows:

RL (%) = 100*[1-(10/25)] = 60%

Using the calculated RL (60%) and figure 5.2 in Part III of the

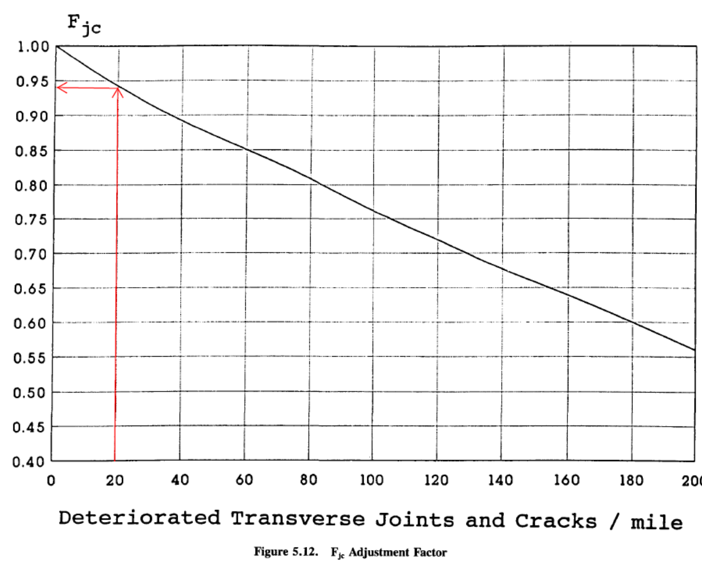

Figure 16. Figure 5.12 from Part III of 1993 AASHTO Guide used to determine F_{jc} for Bonded Overlays.

1993 AASHTO Guide (see figure 17), determine the CF. As shown in figure 17, the CF can be approximated to be 0.92. The effective thickness of the existing concrete slab calculated with the RL method is as follows:

$$D_{eff} = CF*D = (0.92)*(8) = 7.36 \text{ in.}$$

As noted above in Section 2.1, Background of Design Methodologies, the Condition Survey and the Remaining Life methods yield slightly different estimates. Both methods were outlined in this example for illustrational purposes, but designers should select the most feasible method based on the available information.

Step 3. Compute D_{ol}

Compute the required concrete overlay thickness using the 1993 AASHTO Guide equation for bonded overlays over existing concrete pavements:

- D_{eff} calculated with the Condition Survey Method:

  $D_{ol} = D_f - D_{eff} = 11.30 – 7.44 = 3.86$ in.

- D_{eff} calculated with the Remaining Method:

  $D_{ol} = D_f - D_{eff} = 11.30 – 7.36 = 3.94$ in.

Rounding to the nearest 0.5 inch, an overlay thickness of 4.0 in. may be used for this example. Additional design features are discussed in Section 5.1.6, Summary of Results.

5.1.3. 1993 AASHTO Guide: Critical Design Variables

As mentioned above, the most sensitive variables for the 1993 AASHTO Guide method include the traffic, load transfer coefficient, drainage coefficient, and the modulus of rupture. The following explains how the overlay design for this example is affected by changing two of these variables.

Effect of Changing Design Life/Traffic

If the overlay design life is changed from 20 to 30 years, the ESALs increase from 24,780,000 to 41,370,000. This changes the required slab thickness (D_f) in Step 1 from 11.3 to 12.2 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = D_f - D_{eff} = 12.2 – 7.40 = 4.80 \text{ in.}$$

The change in design life increases the required overlay thickness by approximately 1.0 in. (with rounded thicknesses changing from 4.0 to 5.0 in.).

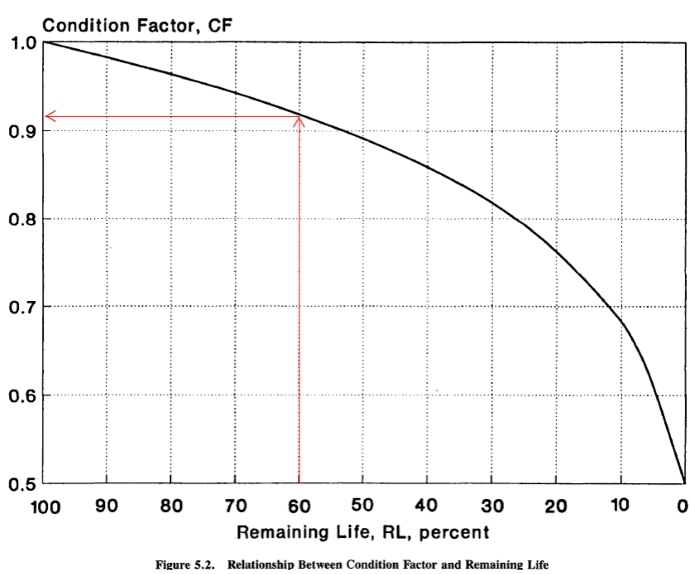

Figure 17. Figure 5.2 in Part III of the 1993 AASHTO Guide to Determine CF.

Effect of Changing Concrete Strength

If the existing pavement's concrete strength is changed to a modulus of rupture of 650 psi and an elastic modulus of 4,100,000 psi, the required slab thickness (D_f) from Step 1 changes from 11.3 to 12.0 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = D_f - D_{eff} = 12.00 – 7.40 = 4.60 \text{ in.}$$

The change in concrete strength increases the required overlay thickness by approximately 1.0 in. (with rounded thicknesses changing from 4.0 to 5.0 in.).

5.1.4. AASHTO Pavement ME Design Guide

The analysis for this example was conducted using AASHTOWare Pavement ME Design and the project description and inputs provided above in Section 5.1.1, Scenario.

Step 1. Input General Information and Performance Criteria

To begin a design for a bonded overlay of concrete pavement, the General Information menu in AASHTOWare Pavement ME Design is used to enter the following inputs:

- Design type: Overlay.
- Pavement type: Bonded PCC/JPCP.
- Design life: 20 years.
- Estimated construction date for the existing pavement: August 1981.
- Estimated construction date for the proposed overlay: September 2011.
- Expected date for overlay opening to traffic: October 2011.

Next, the Performance Criteria inputs for the proposed overlay are defined. In this case, AASHTOWare Pavement ME Design default thresholds for JPCP are used for smoothness/terminal IRI (172 in./mi), JPCP transverse cracking (% slabs cracked, 15), and mean joint faulting (0.12 in.). The reliability is also specified for each performance indicator; in this case, 95% is used.

Step 2. Input Traffic Data

Next, the main Traffic screen is used to enter the following inputs:

- Initial two-way AADTT: (AADT*%Trucks): 16,800*0.20 = 3,360.
- Number of lanes: two lanes each direction.
- Directional distribution factor (%): 50.
- Lane distribution factor (%): 90.
- Operational speed (mph): 60.

AASHTOWare Pavement ME Design default values (Level 3) based on nationally developed distributions from the LTPP database are used for the following traffic inputs (load spectra):

- Traffic volume adjustment factors:
  - Vehicle class distribution.*
    - Traffic growth.**
  - Monthly vehicle distribution.
  - Hourly truck distribution.
- Axle load distributions.
- General traffic inputs (axle configuration, lateral wander, and wheelbase).

*For the Vehicle class distribution, the default distribution is loaded according to the road functional classification; in this example it is selected to be Principal Arterials (Interstate and Defense), and the TTC group is selected to be TTC11 for a major multi-trailer truck route.

** For the traffic growth, a rate of 2.0% (compound growth) is used for all vehicle classes in this example.

Step 3. Input Foundation Support, Design Properties, and Rehabilitation

The Foundation Support menu provides the option to have AASHTOWare Pavement ME Design estimate the modulus of subgrade reaction (default) or to enter it manually. Note that if a value is to be entered manually, AASHTOWare Pavement ME Design requires the dynamic k-value, which is determined through deflection testing and backcalculation. In this example, the option to have AASHTOWare Pavement ME Design calculate the modulus of subgrade reaction is used.

Figure 18 shows a screen capture of the Design Properties menu. For bonded overlays of concrete pavement, the JPCP design inputs entered correspond to the existing pavement design features. For this example, the existing concrete pavement transverse joint spacing is 15 ft, and there are dowel bars 1.25 in. in diameter every 12 in.

The existing PCC-base interface conditions are also defined in the Design Properties menu. As shown in figure 18, the erodibility index for the existing base is entered, and in this case the existing lime-stabilized subgrade was classified as "Erosion

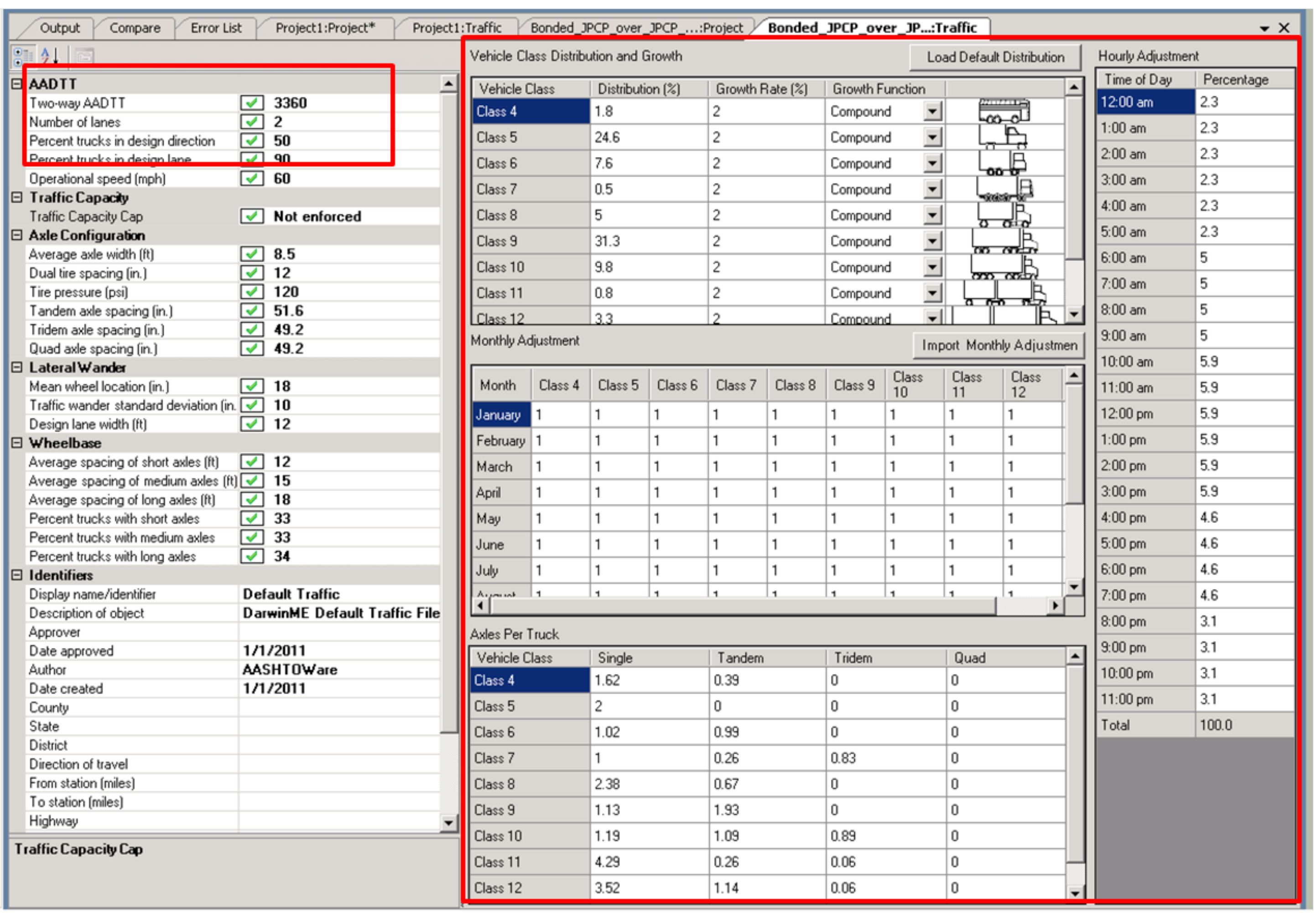

Figure 18. Screen Capture of AASHTOWare Pavement ME Design JPCP Design Properties Menu.

resistant (3)”. For bonded overlays over concrete pavements, the “PCC-base contact friction” value is selected to be “No friction” for the existing pavement (PCC slab)–lime-stabilized subgrade (base) interface condition, indicating that the two layers are unbonded. Other base types, such as asphalt or cement treated bases, are more likely to be bonded to the existing concrete slab. AASHTOWare Pavement ME Design allows users to analyze these cases using the “Full friction contact” input and indicating whether the bond will remain for the design of the overlay or weaken after a period of time under traffic and weather conditions.

Next, the Rehabilitation menu is used when the existing pavement is repaired before the rehabilitation/restoration activities (bonded overlay). This menu is not applicable to this scenario, so the “0” default values are used.

Step 4. Input Climate Data

The location for this example is Fort Worth, Texas. The main Climate screen is used to do the following:

- Create a new climatic data file. For this example, data from the Dallas-Fort Worth International Airport weather station were used.
- Enter the annual average water table depth: 10 ft.

Step 5. Input Pavement Structural Layers

The Pavement Structure menu is used to define the pavement system layers and enter each layer’s material properties. The specific material inputs for each layer are described below.

Overlay Layer Properties

The proposed concrete overlay layer is defined in terms of general (PCC), thermal, mix, shrinkage, and strength properties. An overlay thickness of 2 in. is used for the first trial design. Typical values for concrete pavements are used for the General properties such as the Poisson’s ratio (0.20) and unit weight (150 pcf). Default values in AASHTOWare Pavement ME Design are used for the Thermal properties except for CTE, which in this example is 4.5 (10^{-6}/°F).

NOTE: AASHTOWare Pavement ME Design is currently limited to the analysis of a minimum combined thickness for the existing pavement and the overlay of 6 in. for JPCP analysis.

Inputs for mix properties are project-specific and are obtained from mix designs and specifications. For this example, these include cement type (Type I) and content (600 lb/yd^3), water/cement ratio (0.42), and aggregate type (limestone). In this example, Level 3 inputs are used for strength properties, with a modulus of rupture of 680 psi for the proposed overlay.

Existing Concrete Pavement Layer Properties

Similarly, the Pavement Structure menu is used to define the existing concrete pavement layer in terms of general (PCC), thermal, mix, shrinkage, and strength properties. The existing pavement thickness is input (8 in. for this example). Typical values for concrete pavements are used for the general properties such as the Poisson’s ratio (0.20) and unit weight (150 pcf), and AASHTOWare Pavement ME Design default values are used the thermal properties, except for CTE, which in this example is 4.5 (10^{-6}/°F). Typical local agency values for existing concrete are used for mix properties as described for the concrete overlay layer. For the strength properties, the modulus of rupture of 740 psi estimated from compressive tests is used.

NOTE: A key reference on concrete material properties is the FHWA Integrated Materials and Construction Practices for Concrete Pavement Manual (2007). This document may be accessed online at http://www.cptechcenter.org/publications/imcp.

Base and Subgrade Materials Layer Properties

The Pavement Structure menu is also used to define the base and subgrade materials. The inputs for the lime-stabilized subgrade include the backcalculated resilient modulus (58,000 psi) and thickness (6 in.). Default/typical values for lime-stabilized materials are used for the rest of the inputs in this example. The inputs for the subgrade soils include Level 3 inputs, such as the AASHTO soil classification from the soil survey (A-5) and the subgrade resilient modulus (7,000 psi). Note that the backcalculated subgrade resilient modulus (20,000 psi) is multiplied by 0.35 to adjust to a laboratory resilient modulus, which is the corresponding input to AASHTOWare Pavement ME Design.

Step 6. Run Analysis and Evaluate Results

At this point the AASHTOWare Pavement ME Design analysis is run, and results predict that an overlay thickness of 2 in. will perform satisfactorily in terms of smoothness, faulting, and percent of slabs cracked. Figure 19 summarizes performance criteria at the specified reliability of 95% for this run. Figure 20 through figure 22 show the performance prediction plots for faulting, cracking, and smoothness/IRI for the 2 in. overlay.

5.1.5. AASHTO Pavement ME Design Guide: Critical Design Variables

Effect of Changing Coefficient of Thermal Expansion

CTE is considered a critical design variable for bonded overlays of existing concrete pavements in the AASHTO Pavement ME Design Guide. If the CTE for this example is changed from 4.5 to 6.1 (10^{-6}/°F) for both the overlay and existing pavement layers, the original 2 in. thick overlay design would no longer

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	117.67	95.00	99.99	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	100.00	Pass
JPCP transverse cracking (percent slabs)	15.00	6.71	95.00	99.99	Pass

Figure 19. AASHTOWare Pavement ME Design Distress Prediction Summary for 2 in. Overlay.

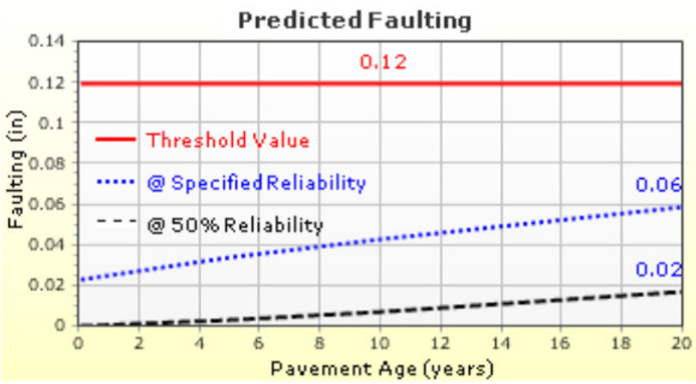

Figure 20. AASHTOWare Pavement ME Design Predicted Faulting Plot for 2 in. Overlay.

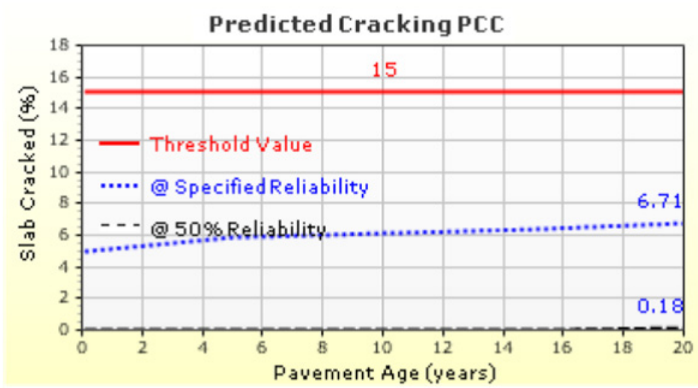

Figure 21. AASHTOWare Pavement ME Design Predicted Cracking Plot for 2 in. Overlay.

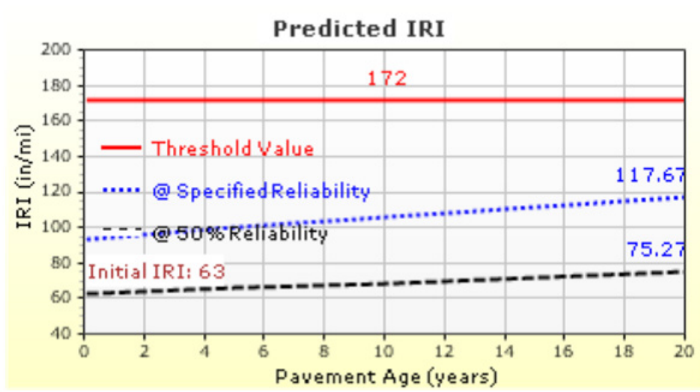

Figure 22. AASHTOWare Pavement ME Design Predicted IRI Plot for 2 in. Overlay.

Table 10. Summary of Results.

Method	Scenario	Thickness(in.)
1993 AASHTO Guide	Original scenario	4.0
	Changing design life (from 20 to 30 years)	5.0
	Decreasing concrete strength (MR and E)	5.0
AASHTO Pavement ME Design Guide	Original scenario	2.0
	Changing CTE from 4.5 to 6.1 (10^{-6}/°F) for both existing pavement and proposed overlay	3.0
	Using a different CTE (10^{-6}/°F) for proposed overlay	3.0

be valid. As shown in figure 23, AASHTOWare Pavement ME Design predicts slabs cracked to be 29.91% at 95% reliability with the change in concrete CTE. Figure 24 shows that a 3 in. overlay is more suitable for this scenario.

Effect of Changing Overlay Coefficient of Thermal Expansion

Another example of the CTE effect in overlay design is when it is not possible to use the same aggregate type for the overlay, and therefore the overlay design is analyzed for a CTE value different from the original concrete. The CTE value for this example is changed to 6.1 (10^{-6}/°F) for the overlay only, and the CTE value for the existing concrete is kept the same, 4.5 (10^{-6}/°F). Figure 25 shows that AASHTOWare Pavement ME Design predicts 56.86% slabs cracked at 95% reliability for this scenario. Figure 26 shows that a 3 in. overlay is more suitable for this scenario.

5.1.6. Summary of Results

Overlay thicknesses of 4.0 in. and 2.0 in. were calculated for the standard case examples with the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide, respectively. For this overlay type, a bonded overlay of existing concrete pavement, joints are matched to the existing section. Transverse joints are cut to the full depth of the overlay plus 0.5 in.,

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	137.06	95.00	99.73	Pass
Mean joint faulting (in.)	0.12	0.09	95.00	99.59	Pass
JPCP transverse cracking (percent slabs)	15.00	29.91	95.00	46.58	Fail

Figure 23. AASHTOWare Pavement ME Design Distress Prediction Summary for CTE: 6.1 (10-6/°F) and 2 in. Overlay.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	136.22	95.00	99.76	Pass
Mean joint faulting (in.)	0.12	0.09	95.00	99.58	Pass
JPCP transverse cracking (percent slabs)	15.00	12.76	95.00	97.84	Pass

Figure 24. AASHTOWare Pavement ME Design Distress Prediction Summary for CTE: 6.1 (10-6/°F) and 3 in. Overlay.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	120.07	95.00	99.98	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	99.99	Pass
JPCP transverse cracking (percent slabs)	15.00	56.86	95.00	1.52	Fail

Figure 25. AASHTOWare Pavement ME Design Distress Prediction Summary for 2 in. Overlay. Overlay and Existing Pavement CTE: 6.1 and 4.5 (10-6/°F), respectively.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	120.67	95.00	99.98	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	99.99	Pass
JPCP transverse cracking (percent slabs)	15.00	14.37	95.00	95.95	Pass

Figure 26. AASHTOWare Pavement ME Design Distress Prediction Summary for 3 in. Overlay. Overlay and Existing Pavement CTE: 6.1 and 4.5 (10-6/°F), respectively.

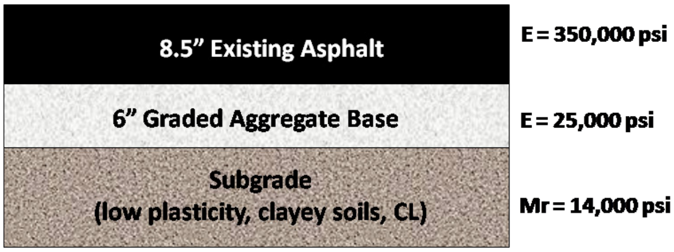

Figure 27. Summary of Existing Pavement Cross-Section.

and longitudinal joints are cut to at least half the thickness of the overlay. Note that some agencies recommend sawing longitudinal joints to the full depth of the overlay plus 0.5 in. as well. At this point in the overlay design process, the next steps are conducting mix designs and assembling surface preparation specifications to ensure the new concrete bonds to the existing concrete layer.

5.2. Bonded Overlay over Existing Asphalt Pavement

5.2.1. Scenario

An existing asphalt pavement along a four-lane divided State Highway is approximately 15 years old and scheduled for rehabilitation. The existing pavement is 8.5 in. thick over 6 in. of graded aggregate base. Lanes are 12 ft wide with 2 ft paved asphalt shoulders. There is moderate to severe rutting throughout the section, particularly at the intersections. Rutting and other distresses are to be addressed by milling 2 in. before applying an overlay. A bonded concrete overlay is one of the rehabilitation alternatives under consideration and needs to be designed. Additional design information is as follows:

Historical Records

- Soil survey indicates that subgrade materials consist mainly of low-plasticity, clayey soils (CL).

Deflection Testing Results (FWD)

- Back calculated moduli, E (psi) for asphalt, base, and subgrade: 350,000, 25,000, and 14,000, respectively.
- Composite modulus of subgrade reaction (k-value) at the bottom of the asphalt (psi/in.): 500.

Distress Survey Results

- Moderate fatigue cracking on both wheel paths.
- Moderate/severe rutting at signalized intersections.

Traffic

- Design life (years): 20.
- Two-way (ADT): 2,500.
- Directional distribution factor (%): 50.
- Design lane distribution factor (%): 100.
- Growth rate (%): 2.0.
- Percent trucks (%): 2.0.
- Truck factor (ESALs/truck): 1.7.

Climate

Location: Denver, Colorado.

Proposed Overlay

- Concrete modulus of elasticity, E (psi): 3,500,000.
- Average 28-day third point flexural strength (psi): 650.
- CTE (10^{-6}/°F): 5.5.

The following section illustrates how to perform the overlay design for this example using the ACPA BCOA Thickness Designer.

5.2.2. ACPA BCOA Thickness Designer

This method consists of an iterative design process in which the proposed overlay thickness is calculated and the appropriateness of the assumed slab size and fiber content are evaluated. The steps involved in using the ACPA BCOA Thickness Designer (shown in figure 28) are listed in the following sections. Additional information about each input can be sought by clicking the "Help" button.

Step 1. Input Traffic Data

Design ESALs serve as the main traffic input. This number can be entered directly into the input box or calculated by clicking the "Estimate ESALs" button. The necessary inputs for estimating ESALs are given in Section 5.2.1 and for this example yield 384,451 ESALs.

Step 2. Input Failure Criterion

In this example, the input for maximum allowable percent slabs cracked is 15% at a reliability of 80%. This criterion represents a 20% probability that more than 15% of the slabs will crack before the cumulative traffic has been reached.

Step 3. Select Project Location

In order to calculate the effective temperature gradient (°F/in.), a city in close proximity to the project site can be selected. In this example, Denver is selected, and the BCOA calculates the effective temperature gradient internally.

Step 4. Input Existing Pavement Structure Details

After milling, the remaining asphalt thickness is 6.5 in. Based on deflection testing results, the existing asphalt modulus of elasticity was found to be 350,000 psi, and the composite modulus of subgrade reaction, which incorporates the subgrade and base, is 500 pci.

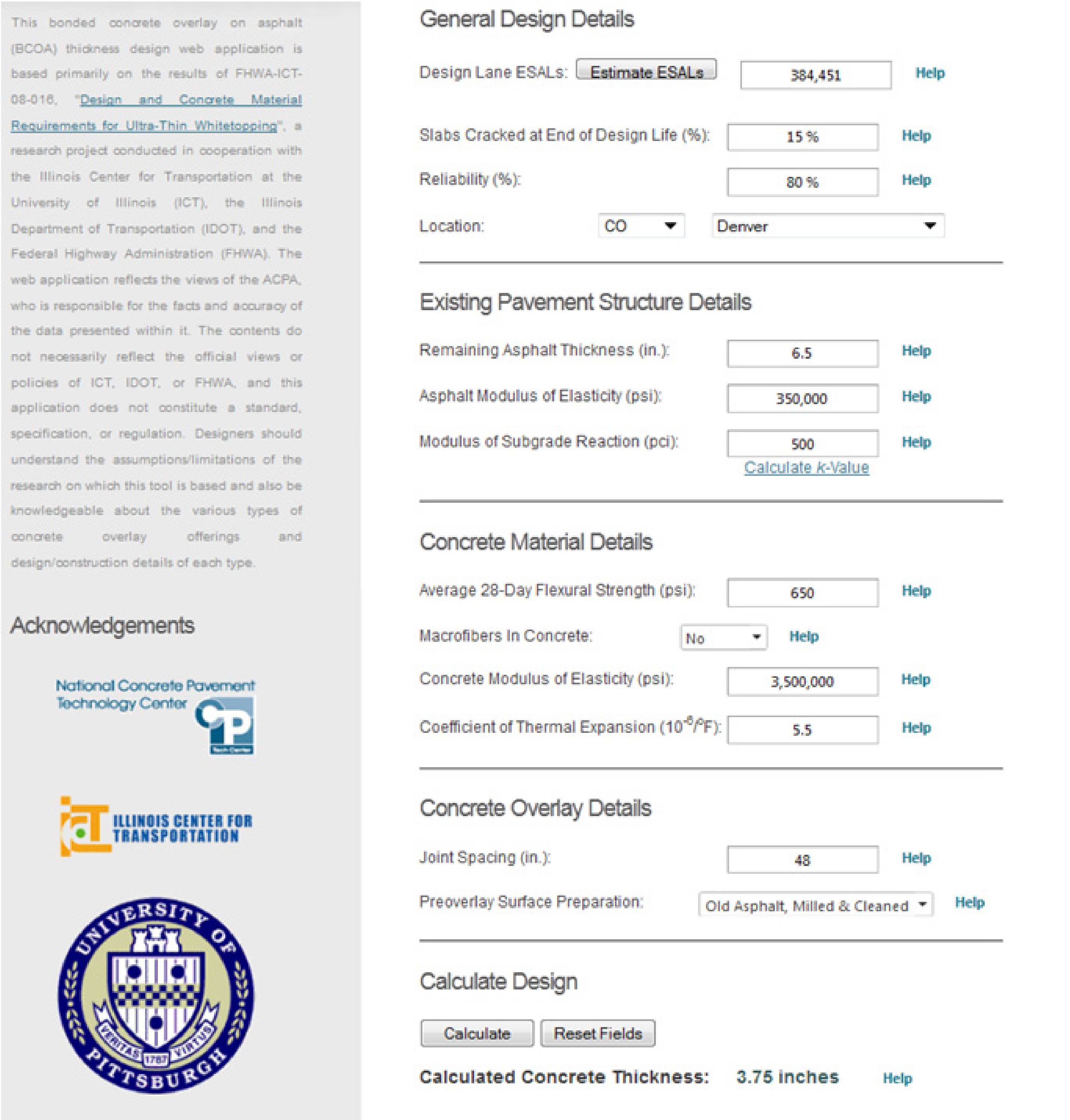

Figure 28. Screen Capture of ACPA BCOA Thickness Designer.

Step 5. Input Concrete Material Details

The average 28-day flexural strength (psi), concrete modulus of elasticity (psi), and CTE (10^{-6}/°F) for this example are 650, 3,500,000, and 5.5, respectively. The use of macrofibers, which is not applicable in this case, can also be entered.

Step 6. Input Concrete Overlay Details

The joint spacing and pre-overlay surface preparation must be input as well. In this example, a joint spacing of 48 in. is proposed. The "Old Asphalt, Milled & Clean" option is selected as well.

Step 7. Evaluate Results

Once all inputs have been entered, the "Calculate" button can be clicked to determine the effective overlay thickness. As shown in figure 28, an overlay thickness of 3.75 in. is calculated, and, therefore, an overlay 4.0 in. thick with 48 in. joint spacing provides a satisfactory design for this example.

5.2.3. ACPA BCOA Thickness Designer: Critical Design Variables

As previously mentioned, Riley (2006b) and Roesler et al. (2008) list several variables as critical for this method. The sensitivity of these variables, and how they affect an overlay design, is important for designers to recognize and understand. For instance, the following paragraphs discuss how the overlay design for this example is affected by changing two critical variables: asphalt stiffness (modulus of elasticity) and effective temperature gradient.

Effect of Changing Asphalt Stiffness

If the existing asphalt layer modulus of elasticity for the previous example is changed from 350,000 psi (representative of asphalt in a moderate condition with some level of structural distress) to 500,000 psi (representative of asphalt in good condition) the calculated overlay thickness would be reduced from 3.75 to 3 in. This difference emphasizes the importance of accurately characterizing the existing asphalt layer condition.

Effect of Changing Slab Temperature Differentials

Similarly, a change in slab temperature differentials for the original example also affects the overlay design significantly. For example, if the selected city is Chicago instead of Denver, the slab temperature gradients change accordingly (°F/in.). In this case, the calculated overlay thickness would be reduced from 3.75 to 3 in.

5.2.4. Summary of Results

A bonded concrete overlay 4.0 in. thick with a joint spacing of 48 in. was determined for this example using the ACPA BCOA Thickness Designer. For this type of overlay, transverse joints are cut to a depth of T/4 but no less than 1.25 in., and longitudinal joints are cut to T/3 of the overlay (Harrington et al. 2008). The next step for this overlay design process is to conduct concrete mix designs and assemble surface preparation and repair specifications.

Table 11. Summary of Results.

Method	Scenario	Design
ACPA BCOA Thickness Designer	Original scenario	4.0 in. thickness 48 in. joint spacing
	Changing asphalt stiffness (from 350,00 to 500,000 psi)	3 in. thickness 48 in. joint spacing
	Changing project location/ climate (slab temperature differential, Denver vs. Chicago)	3 in. thickness 48 in. joint spacing

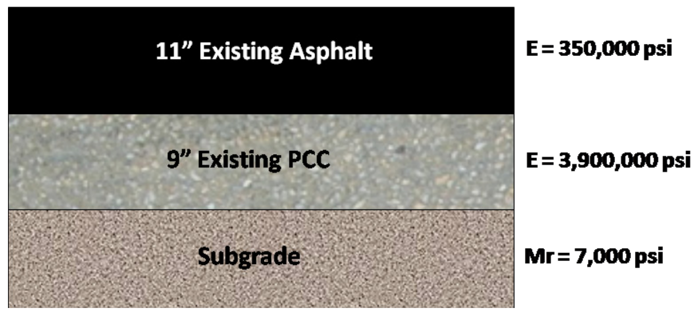

Figure 29. Summary of Existing Pavement Cross-Section.

5.3. Bonded Overlay over Existing Composite Pavement

5.3.1. Scenario

An existing composite pavement along a State Highway is scheduled for rehabilitation. The exact history of the existing pavement is not known, but it is estimated that the original concrete pavement is at least 50 years old and has been overlaid with asphalt numerous times. The existing asphalt layer is currently 11 in. thick over the 9 in. concrete pavement on natural subgrade. Lanes are 12 ft wide with 4 ft paved asphalt shoulders. There is moderate rutting and some load-associated cracking throughout the section. Rutting and other distresses are to be addressed by milling 5 in. before applying an overlay. A bonded concrete overlay is one of the rehabilitation alternatives being considered. Additional design information is as follows:

Deflection Testing Results

- Backcalculated moduli, E (psi) for asphalt, concrete, and subgrade: 350,000, 3,900,000, and 7,000, respectively.
- Composite modulus of subgrade reaction, k-value at the bottom of the asphalt (psi/in.): 800.

Distress Survey Results

- Low-severity fatigue cracking and moderate rutting.
- Distressed surface materials to be removed by milling.

Traffic

- Design life (years): 20.
- Two-way ADT: 2,500.

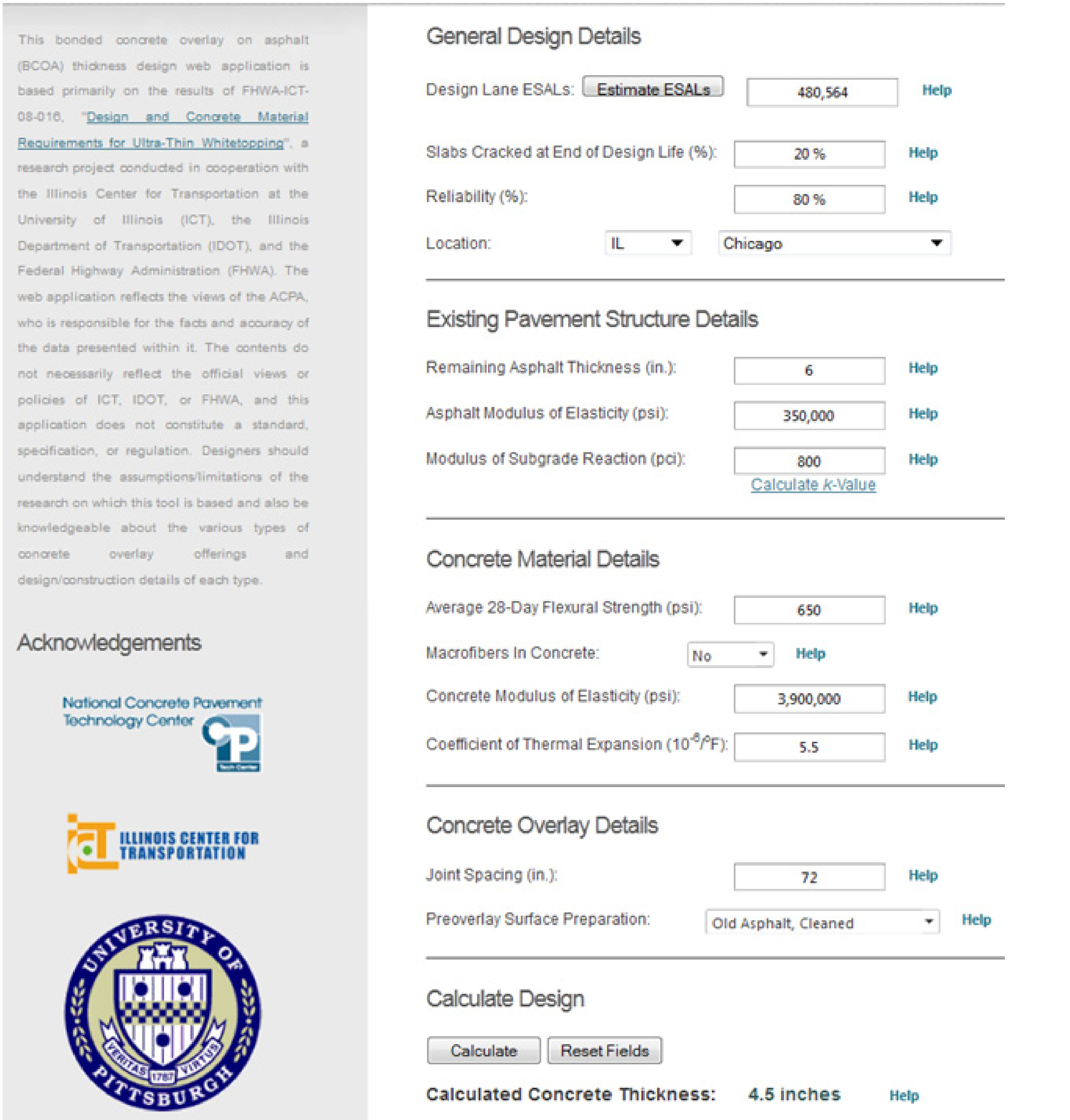

Figure 30. Screen Capture of ACPA BCOA Thickness Designer.

- Directional distribution factor (%): 50.
- Design lane distribution factor (%): 100.
- Growth rate (%): 2.0.
- Percent trucks (%): 2.5.
- Truck factor (ESALs/truck): 1.7.

Climate

- Location: near Chicago, Illinois.

Proposed Overlay

- Concrete modulus of elasticity, E (psi): 3,900,000.
- Average 28-day third point flexural strength (psi): 650.

- CTE (10^{-6}/°F): 5.5.

The following section illustrates how to perform the overlay design for this example using the ACPA BCOA Thickness Designer.

5.3.2. ACPA BCOA Thickness Designer

This method consists of an iterative design process in which the proposed overlay thickness is calculated and the appropriateness of the assumed slab size and fiber content are evaluated. The steps involved in using the ACPA BCOA Thickness Designer (shown in figure 30) are listed in the following sections. Additional information about each input can be sought by clicking the "Help" button.

Step 1. Input Traffic Data

Design ESALs serve as the main traffic input. This number can be entered directly into the input box or calculated by clicking the "Estimate ESALs" button. The necessary inputs for estimating ESALs are given in Section 5.3.1 and for this example yield 480,564 ESALs.

Step 2. Input Failure Criterion

In this example, the input for maximum allowable percent slabs cracked is 20% at a reliability of 80%. This criterion represents a 20% probability that 20% of the slabs will crack before the cumulative traffic has been reached.

Step 3. Select Project Location

In order to calculate the effective temperature gradient (°F/in.), a city in close proximity to the project site can be selected. In this example Chicago is selected, and the BCOA calculates an effective temperature gradient internally.

Step 4. Input Existing Pavement Structure Details

After milling, the remaining asphalt thickness would be 6.0 in. Based on deflection testing results, the existing asphalt modulus of elasticity was found to be 350,000 psi.

For this example, it is assumed that the existing concrete pavement acts as a very strong subbase. Therefore, a combined k-value for the existing subgrade together with the existing concrete subbase must be determined. Based on backcalculation results and the maximum value for composite pavement analysis, the composite modulus of subgrade reaction (k-value at the bottom of the asphalt) for this example is estimated at 800 psi/in.

Step 5. Input Concrete Material Details

The inputs required for this step are specific to the new concrete overlay. If no project-specific information is available, designers may base their inputs on typical values used by the local agency. The inputs include the elastic modulus (3.9 million psi), average 28-day third point flexural strength (650 psi), and CTE (5.5×10^{-6}/°F). The use of macrofibers can also be entered.

Table 12. Summary of Results.

Method	Scenario	Design
ACPA BCOA Thickness Designer	Original scenario	4.5 in. thickness 72 in. joint spacing
	Changing joint spacing (from 72 in. to 48 in.)	3 in. thickness 48 in. joint spacing
	Using macrofibers in concrete overlay	3 in. thickness 72 in. joint spacing

Step 6. Input Concrete Overlay Details

The joint spacing and pre-overlay surface preparation must be input as well. In this example, a joint spacing of 72 in. is proposed. The "Old Asphalt, Milled & Clean" option is selected as well.

Step 7. Evaluate Results

Once all inputs have been entered, the "Calculate" button can be clicked to determine the effective overlay thickness. As shown in figure 30, an overlay thickness of 4.5 in. is calculated, and therefore an overlay 4.5 in. thick with 72 in. joint spacings provides a satisfactory design for this example.

5.3.3. ACPA BCOA Thickness Designer: Critical Design Variables

As mentioned above, Riley (2006b) and Roesler et al. (2008) list several variables as critical for this method. The sensitivity of these variables and how they affect an overlay design is important for designers to recognize and understand. As an example, the following discusses how the overlay design for this example is affected by changing two critical variables: joint spacing and structural fibers.

Effect of Changing Joint Spacing

If the joint spacing is changed to 48 in., the required slab thickness is 3 in. For this case, a slab size of 3 in. thick with 48 in. joint spacing provides a satisfactory design.

Effect of Using Structural Fibers

If macrofibers are used in this design at a 20% residual strength ratio, the slab thickness could be reduced to 3 in.

5.3.4. Summary of Results

A bonded overlay 4.5 in. thick with a joint spacing of 72 in. was determined for this example using the BCOA ACPA method. For this type of overlay, transverse joints are cut to a depth of T/4 but no less than 1.25 in. Longitudinal joints are cut to T/3 of the overlay. The next step for this overlay design process is to conduct concrete mix designs and assemble surface preparation and repair specifications.

5.4. Unbonded Overlay over Existing Concrete Pavement

5.4.1. Scenario

A JPCP along a rural principal arterial built in 1986 is scheduled for rehabilitation. The existing pavement is 10 in. thick over 10 in. of crushed aggregate base on compacted subgrade. Lanes are 12 ft wide, with 30 ft transverse joint spacing and 2 ft wide asphalt shoulders. A detailed pavement evaluation revealed that the existing concrete is in fair to poor condition and, as a result, an unbonded concrete overlay is the primary rehabilitation option. In order to effectively design the unbonded overlay, the following design information has been gathered:

Historical Records

- 1 in. dowel bars at transverse joints, 12 in. spacing.
- Soil survey indicates that subgrade materials consist mainly of clayey soils (A-6).
- Estimated E (psi) for concrete, base, and subgrade: 4,200,000, 25,000, and 14,000, respectively.

Deflection Testing Results

FWD testing for joint load transfer at representative joints/cracks averaged a LTE of 85%.

Effective dynamic k-value (psi/in.): 325.

Distress Survey Results

- Estimated number of unrepaired spalling areas, deteriorated transverse joints, and cracks: 175 per mile, i.e., 1 mid-panel crack per slab.
- Low- to moderate-severity concrete durability problems. "D" cracking along transverse and longitudinal joints.
- Severe spalling to be repaired by filling in with asphalt material. Widespread repairs specified for centerline joint as well as transverse joints.

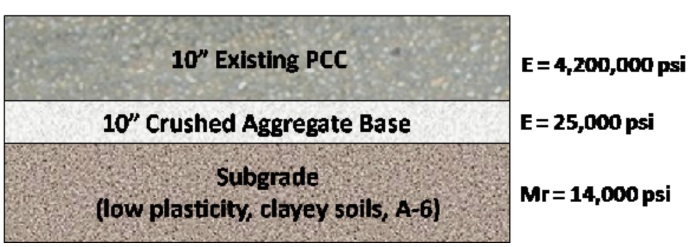

Figure 31. Summary of Existing Pavement Cross-Section.

Traffic

- Future ESALs (20-year design life): 11,470,000.
- Initial 2-way AADTT: 1,400; Growth rate: 2% (compound).
- Existing roadway: 2 lanes (1 lane each way).
- Directional distribution: 50%, Design lane distribution factor: 100%.

Climate

- Location: Kansas City, Missouri.
- Annual average water table depth: 12 ft.

Proposed Overlay

- Elastic modulus, E (psi) for concrete: 4,800,000.
- 28-day flexural strength (psi): 650.
- CTE (10^{-6}/°F): 5.5.
- Joint spacing: 12 ft.

The following sections illustrate how to perform the overlay design for this example using both the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide.

5.4.2. 1993 AASHTO Guide

The design of unbonded overlays over existing concrete pavements using the 1993 AASHTO Guide is based on the following equation:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})}$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

Step 1. Determine D_f

Determine D_f using the rigid pavement design equation or nomograph in figure 3.7 in Part II (pg. II-45) of the 1993 AASHTO Guide. Table 13 summarizes the inputs used to determine D_f. Use of the nomograph yields a required slab thickness (D_f) of 12.0 in.

Step 2. Determine D_{eff}

Determine D_{eff} using the Condition Survey method.

NOTE: The Remaining Life method is not applicable to pavements with durability problems.

Condition Survey Method

Based on the distress survey results, determine the adjustment factor to use in the following equation:

$$D_{eff} = F_{jcu} * D$$

Where, D = existing slab thickness (in.), 10 in., F_{jcu} = joint

Table 13. Summary of Design Inputs for D_f.

Input (Units)	Calculations/Estimates	Value
Effective static k-value, psi/in.	Effective dynamic k-value (from deflection testing) / 2 = 1000 / 2	163
E, Concrete elastic modulus, psi	For proposed overlay: estimated from project mix designs and specifications	4,800,000
S'_c, Concrete modulus of rupture, psi		650
J, Load transfer factor	Based on Table 2.6 in Part II of the 1993 AASHTO Guide, for a JPCP overlay with no dowels, and asphalt shoulders	3.8
C_d, Drainage coefficient	Typically 1.0 for poor subdrainage conditions	1.0
Δp, Design serviceability loss	(Initial Serviceability: 4.5) – (Terminal Serviceability: 2.5)	2.0
R, Reliability (%)	Typical value for high-traffic concrete overlay	95
S_o, Standard deviation	Typical value for high-traffic concrete overlay	0.39
W_{18}, Future traffic (ESALs)	ESAL calculations according to local/ regional load equivalency factors	11,470,000

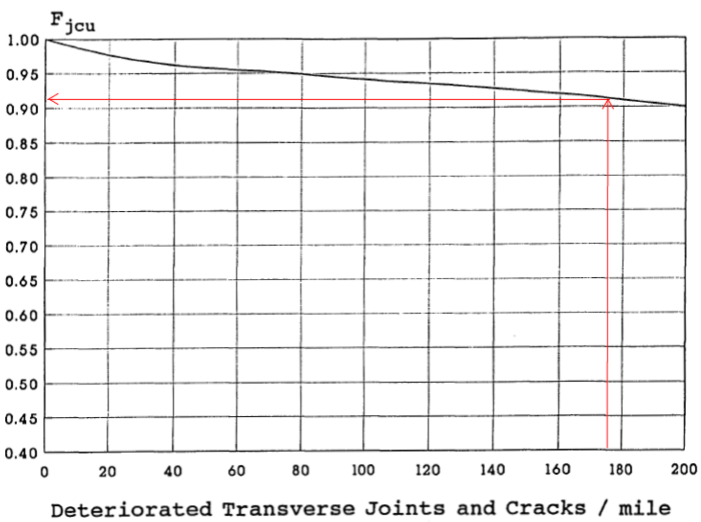

Figure 5.13. F_{jcu} Adjustment Factor for Unbonded JPCP, JRCP, and CRCP Overlays

Figure 32. Figure 5.13 from Part III of the 1993 AASHTO Guide Used to Determine F_{jcu} for Unbonded Overlays.

and crack adjustment factor for unbonded overlays, 0.91. This value is determined using figure 5.13 in Part III of the 1993 AASHTO Guide (see figure 32) and the total number of unrepaired spalling areas, deteriorated joints, and cracks per mile, which in this case is 175.

NOTE: the D_{eff} equation and the joint and adjustment factors chart in figure 32 are not the same as for the ones used for bonded overlays.

The effective thickness of the existing concrete slab calculated with this method is as follows:

$$D_{eff} = F_{jcu} * D = 0.91*10 = 9.10 \text{ in.}$$

Step 3. Compute D_{ol}

Compute the required concrete overlay thickness using the 1993 AASHTO Guide equation for unbonded overlays over existing concrete pavements:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(12.0^2 - 9.10^2)} = 7.82 \text{ in.}$$

An overlay thickness of 8.0 in. may be used for this example.

Separator Layer

As previously mentioned, the 1993 AASHTO Guide does not account for the structural contribution from the interlayer placed between the existing concrete and the unbonded overlay. Experience has shown that a 1 to 2 in. asphalt interlayer has worked well in unbounded concrete layers. Due to the high load transfer across the joints/cracks, a nonwoven geotextile may be selected as an alternate to the asphalt interlayer, but the required concrete overlay thickness should be increased by 0.5 in. (Hall et al. 2007). Therefore, in this case the overlay thickness would increase to 8.5 in. Additional design features are discussed below in Section 5.4.6, Summary of Results.

5.4.3. 1993 AASHTO Guide: Critical Design Variables

As previously mentioned in this guide, the most sensitive variables for this method when designing unbonded overlays over concrete pavements include traffic, load transfer coefficient, drainage coefficient, modulus of rupture, k-value, and serviceability loss. The following presents how this overlay design example is affected by changing two critical variables: load transfer coefficient and design serviceability loss.

Effect of Changing Load Transfer Coefficient

If dowels are used to improve the load transfer efficiency of the unbonded overlay along with tied concrete shoulders (asphalt shoulders in original design), the load transfer coefficient, J, would change from 3.8 to 2.8 based on table 2.6 in Part II of the 1993 AASHTO Guide. This changes the required slab thickness (D_f) in Step 1 from 12.0 to 10.2 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(12.0^2 - 9.10^2)} = 4.61 \text{ in.}$$

Note that an overlay thickness of 5.0 in. (rounded) is calculated this example if dowels are used. However, from a practical standpoint dowels are not recommended for overlay thicknesses less than 7 in. because the overlay would not provide enough concrete cover above the bars and the use of vibrators in the concrete may interfere with the bars. Therefore, a change in load transfer coefficient, J, will decrease the required overlay thickness by approximately 1.0 in. (with rounded thicknesses changing from 8.0 to 7.0 in.).

Effect of Changing Design Serviceability Loss

If the terminal serviceability were changed from 2.5 to 2.0, the design serviceability loss, Δp, would increase from 2.0 to 2.5. This increase changes the required slab thickness (D_f) calculated in Step 1 from 12.0 to 11.7 in. Repeating Step 3 with the new D_f results in the following overlay thickness:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(11.7^2 - 9.10^2)} = 7.35 \text{ in.}$$

The change in design serviceability loss will decrease the required overlay thickness by approximately 0.5 in. (with rounded thicknesses changing from 8.0 to 7.5 in.).

5.4.4. AASHTO Pavement ME Design Guide

The design process for unbonded overlays of concrete or composite pavements follows the general steps for using the AASHTO Pavement ME Design software described above for bonded overlays in Section 5.1, Bonded Overlay over Existing Concrete Pavement. The traffic and climate inputs are the same as for the design of bonded overlays. The main differences are the design properties and pavement structure inputs, as described in Steps 3 and 5 below.

Step 1. Input General Information and Performance Criteria

To begin a design for an unbonded overlay of concrete pavement, the General Information menu in AASHTOWare Pavement ME Design is used to enter the following inputs:

Design type: Overlay.

- Pavement type: JPCP over JPCP (unbonded).
- Design life: 20 years.
- Estimated construction date for the existing pavement: August 1986.
- Estimated construction date for the proposed overlay: September 2011.
- Expected date for overlay opening to traffic: October 2011.

Next, Performance Criteria menu inputs for the proposed overlay are defined. In this case, the AASHTOWare Pavement ME Design default thresholds for JPCP are used for smoothness/IRI (172 in./mi), % slabs cracked (15), and mean joint faulting (0.12) in. The reliability is also specified for each performance indicator; in this case 95% is used.

Step 2. Input Traffic Data

Next, the main Traffic screen is used to enter the following inputs:

- Initial 2-way AADTT: 1,400.
- Number of lanes: 1-lane each direction.
- Directional distribution factor (%): 50.
- Lane distribution factor (%): 100.
- Operational speed (mph): 60.

AASHTOWare Pavement ME Design default values (Level 3) based on nationally developed distributions from the LTPP database are used for the following traffic inputs (load spectra):

- Traffic volume adjustment factors:
- Vehicle class distribution.*
  - Traffic growth.**
- Monthly vehicle distribution.
- Hourly truck distribution.
- Axle load distribution.
- General traffic inputs (axle configuration, lateral wander, and wheelbase).

*For the vehicle class distribution the road functional classification is selected to be Principal Arterials Others, and the TTC group is selected to be TTC11 for a major multi-trailer truck route.

** For the traffic growth, a rate of 2% (compound growth) is entered for all vehicle classes.

Step 3. Input Foundation Support and Design Features

The Foundation Support menu provides the option to have AASHTOWare Pavement ME Design estimate the modulus of subgrade reaction (default) or have the user enter it manually. Note that if a value is to be entered manually, AASHTOWare Pavement ME Design requires the dynamic k-value, which is determined through deflection testing and backcalculation. In this example, the option to have AASHTOWare Pavement ME Design calculate the modulus of subgrade reaction is used.

Figure 33 shows a screen capture of the Design Features menu. These inputs correspond to the proposed unbonded overlay, including the transverse joint spacing, dowel bar reinforcement diameter and spacing, type of shoulder, and the proposed concrete overlay-base interface.

A joint spacing of 12 ft is initially selected. The recommended joint spacing for unbonded overlays is typically shorter than the spacing for new pavements, which usually ranges from 12 to 15 ft. In addition, the joints in the new overlay do not need to match the existing pavement joint spacing, in this case 30 ft or, if the mid-panel cracks are considered, 15 ft.

No dowels or PCC tied shoulders are included for load transfer in the first iteration for this example, but these factors should be considered if the analysis results indicate excessive faulting. Last in this menu, a “No friction” value is automatically selected as the interface condition that exists between the bottom of the

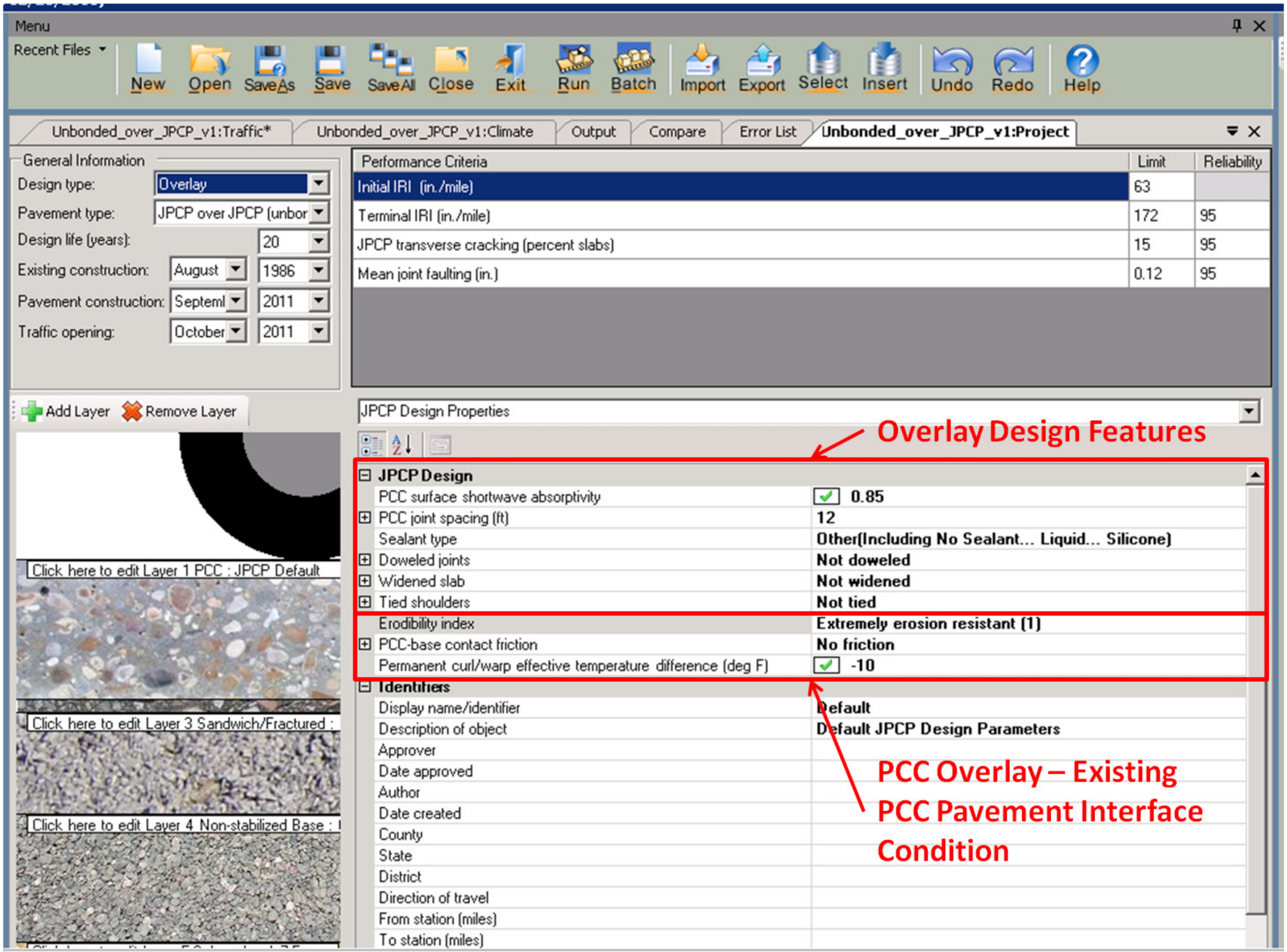

Figure 33. Screen Capture of AASHTOWare Pavement ME Design Properties Menu.

overlay and the surface of the base (existing JPCP), indicating that the two layers are unbonded. The erodibility of the base layer must also be selected.

Step 4. Input Climate Data

The location for this example is Kansas City, Missouri. The main Climate screen is used to do the following:

- Create a new climatic data file. For this example, Kansas City International Airport weather station data were used.
- Enter the annual average water table depth: 12 ft.

Step 5. Input Pavement Structural Layers

The Pavement Structure menu is used to define various layer properties. The material properties inputs for the different pavement layers are described below.

Overlay Layer Properties

The concrete overlay layer is defined in terms of general (PCC), thermal, mix, shrinkage, and strength properties. A thickness of 9.0 in. is used for the first overlay trial design. Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.20) and unit weight (150 pcf). Default values in AASHTOWare Pavement ME Design are used for the thermal properties except for CTE ($5.5x10^{-6}$/°F).

Inputs for mix properties are project-specific and are obtained from mix designs and specifications. These include cement type (Type I) and cementitious material content (500 lb/yd^3), water/cement ratio (0.42), and aggregate type (limestone). Level 3 inputs are used for the strength properties of the proposed overlay, in this case a modulus of rupture of 650 psi.

Existing Concrete Pavement Layer Properties

Similarly, the Pavement Structure menu is used to define the existing concrete pavement layer in terms of general (PCC), mix, strength, and thermal properties. The existing pavement thickness is input in this menu (10 in.). Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.20) and unit weight (150 pcf). For the

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	117.67	95.00	99.99	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	100.00	Pass
JPCP transverse cracking (percent slabs)	15.00	6.71	95.00	99.99	Pass

Figure 34. AASHTOWare Pavement ME Design Distress Prediction Summary for 9.0 in. Unbonded Overlay No Dowels.

strength properties, the estimated modulus of elasticity for the existing pavement is input (4,200,000 psi). AASHTOWare Pavement ME Design default values are used for existing concrete thermal properties.

Asphalt Separation Layer

Unbonded overlays of existing concrete pavements require an interlayer to prevent reflective cracking and to prevent bonding between the two concrete layers. A 1 in. thick asphalt interlayer is used for this example with Level 3 inputs for the asphalt material properties, including asphalt mix volumetrics and mechanical and thermal properties. These inputs are obtained from the typical mixture properties used by each local agency.

A nonwoven geotextile interlayer may be used for this example in lieu of asphalt. As mentioned above and, similar to the 1993 AASHTO Guide, currently there is no option for choosing and characterizing a nonwoven geotextile layer in AASHTOWare Pavement ME Design. It is recommended that an analysis using an asphalt interlayer be performed and the resulting overlay thickness design be increased by 0.5 in. to accommodate increased stresses due to the compliant geotextile layer.

Base and Subgrade Materials Layer Properties

The Pavement Structure menu is also used to define the base and subgrade materials. The inputs for the crushed aggregate base include the backcalculated resilient modulus (25,000 psi) and thickness (10 in.). Default/typical values for crushed gravel materials are used for the rest of the inputs in this example. Level 3 inputs are used for the subgrade soils, which include the soil classification (A-6) and the estimated/representative resilient modulus from historical records for local soils (14,000 psi).

Step 6. Evaluate Results

When the AASHTOWare Pavement ME Design analysis is run, the results predict that an overlay 9.0 in. thick with 12 ft joint spacing and no dowels will perform satisfactorily in terms of smoothness, faulting, and % slabs cracked. Figure 34 shows the summary of performance predictions at the specified reliability of 95% for this run.

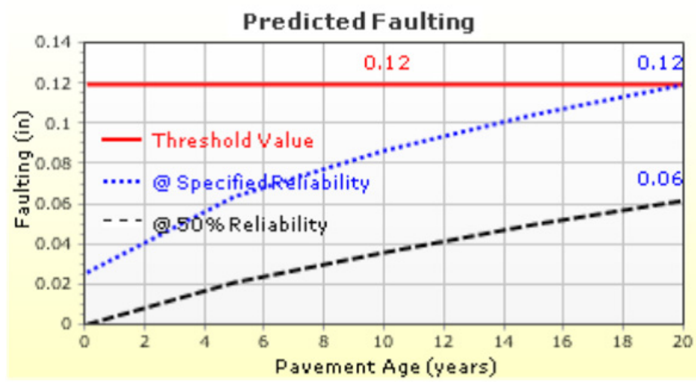

Figure 35. AASHTOWare Pavement ME Design Predicted Faulting Plot for 9.0 in. Unbonded Overlay without Dowels.

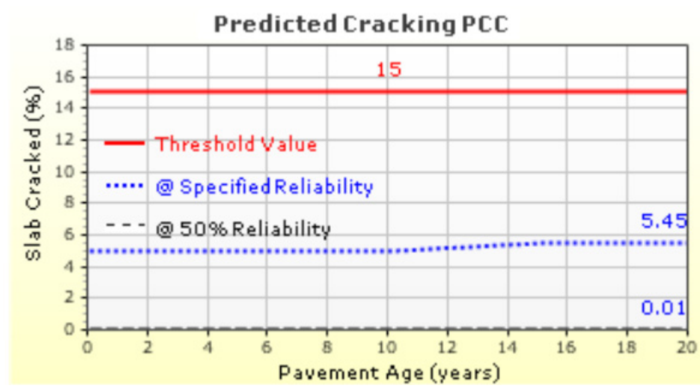

Figure 36. AASHTOWare Pavement ME Design Predicted Cracking Plot for 9.0 in. Unbonded Overlay without Dowels.

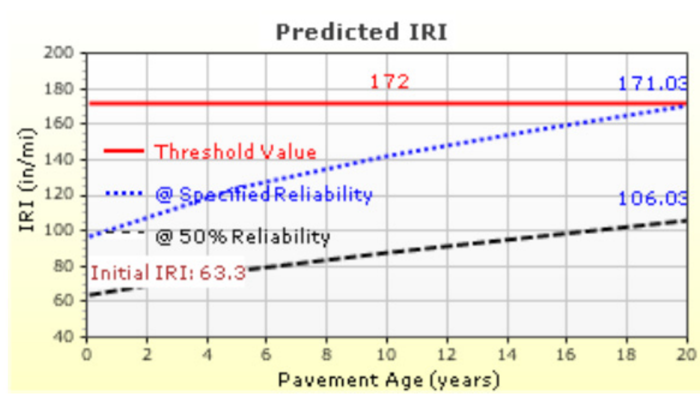

Figure 37. AASHTOWare Pavement ME Design Predicted IRI Plot for 9.0 in. Unbonded Overlay without Dowels.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	117.67	95.00	99.99	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	100.00	Pass
JPCP transverse cracking (percent slabs)	15.00	6.71	95.00	99.99	Pass

Figure 38. AASHTOWare Pavement ME Design Distress Prediction Summary for 7.0 in. Unbonded Overlay with Dowels.

Table 14. Summary of Results.

Method	Scenario	Thickness(in.)
1993 AASHTO Guide	Original scenario	8.0
	Changing load transfer (adding dowels and tied concrete shoulders) (NOTE: calculated thickness of 5.0 in. but for practical purposes recommendation is to use 7.0 in. as a minimum for overlays with dowels)	7.0
	Changing design serviceability loss (terminal psi 2.0 and Δp 2.5)	7.5
AASHTO Pavement ME Design Guide	Original scenario	10.0
	Changing load transfer (adding dowels and asphalt shoulders) (NOTE: thinner overlay is possible but for practical purposes recommendation is to use 7.0 in. as a minimum for overlays with dowels)	7

Figure 35 through figure 37 show the performance prediction plots for faulting, cracking, and smoothness for the 9.0 in. thick overlay with 12 ft joint spacing and without dowels.

5.4.5. AASHTO Pavement ME Design Guide: Critical Design Variables

Effect of Changing Load Transfer

Figure 38 shows the summary of results for the second iteration of this example incorporating 1.5 in. dowels spaced at 12 in. This change allows reducing the overlay thickness to 7 in. Note that a thinner overlay is possible. However, from a practical standpoint dowels are not recommended for overlay thicknesses less than 7 in. because the overlay would not provide enough concrete cover above the bars, and the use of vibrators in the concrete may interfere with the bars.

5.4.6. Summary of Results

Overlay thicknesses of 8.0 in. and 9.0 in. were calculated for the standard case examples using the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide methods, respectively, and with a joint spacing of 12 ft (AASHTOWare Pavement ME Design only). The recommended joint spacing for unbonded overlays is typically shorter than it is for new pavements, which usually ranges from 12 to 15 ft. In addition, the joints in the new overlay do not need to match the existing pavement joint spacing, in this case 30 ft or, if the mid-panel cracks are considered, 15 ft. At this point in the overlay design process, the next steps are conducting mix designs and assembling specifications.

5.5. Unbonded Overlay over Existing Asphalt Pavement

5.5.1. Scenario

An asphalt pavement section along an urban Interstate is scheduled for rehabilitation. The original pavement was built in 1955 and consisted of 4 in. of asphalt over 8 in. of crushed aggregate base on 10 in. of crushed aggregate subbase. Several maintenance overlays (some involving milling) have been applied throughout the years, and the current asphalt thickness is 14 in. The lanes are 12 ft wide, with 10 ft outside shoulders and 4 ft inside shoulders.

A detailed pavement evaluation revealed that the pavement is in fair to poor condition. A project requirement is that the existing roadway profile needs to be maintained in order to minimize impact on bridges and drainage structures. As a result, an unbonded concrete overlay is being considered to make the overlay thickness the same as the asphalt milling depth. This type of project is typically referred to as “mill and inlay” to indicate that the same asphalt thickness that is milled is going to be filled with the overlay (in this case concrete). The following design information has been gathered:

Deflection Testing Results

- Backcalculated E (psi) for asphalt and base/subbase: 310,000 and 23,000, respectively.
- Backcalculated subgrade modulus, Mr (psi): 24,000. Note that for the subgrade resilient modulus (Mr) input to AASHTOWare Pavement ME Design, the backcalculated value is adjusted to represent laboratory conditions. In this case, 0.35*backcalculated Mr (psi): 8,400.

- Effective dynamic k-value (psi/in.): 1,100.

Soil Survey

- AASHTO soil classification: A-7-5.

Distress Survey Results

- Low-severity fatigue cracking and rutting along wheelpaths.
- Moderate longitudinal/transverse cracking.
- Stripping and debonding of the upper layers observed during coring throughout the entire section.

Traffic

- Future ESALs (30-year design life): 13,000,000.
- Initial 2-way AADTT: 1350; Growth rate: 2.3% (linear).
- Existing roadway: 4 lanes (2 lanes each way).
- Directional distribution: 50%; Design lane distribution factor: 85%.

Climate

- Location: Wichita, Kansas.
- Annual average water table depth: 12 ft.

Proposed Overlay

- Modulus of elasticity, E (psi), for concrete: 4,800,000.
- 28-day flexural strength (psi): 650.
- CTE (10^{-6}/°F): 5.5.
- Joint spacing 15 ft.
- 1.25 in. dowels spaced at 12 in.

The following sections illustrate how to perform the overlay design for this example using both the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide.

5.5.2. 1993 AASHTO Guide

The design of unbonded overlays over existing asphalt pavements using the 1993 AASHTO Guide is based on the following equation:

$$D_{ol} = D_f$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.).

For thickness design purposes, the existing asphalt pavement is treated as the base, and the overlay is designed as a new concrete pavement.

Step 1. Determine D_f

Determine D_f using the rigid pavement design equation or nomograph in figure 3.7 in Part II (pg. II-45) of the 1993 AASHTO Guide. Table 9 summarizes the inputs used to determine D_f. Use of the nomograph yields a required slab thickness (D_f) and, in this case, a required overlay thickness (D_{ol}) as well, of 10.5 in.

An overlay thickness of 10.5 in. may be used for this example. Additional design features are discussed below in Section 5.5.6.

5.5.3. 1993 AASHTO Guide: Critical Design Variables

As previously mentioned in this guide, the most sensitive variables for this method when designing unbonded overlays over asphalt pavements include traffic, load transfer, drainage coefficient, modulus of rupture, and composite k-value. The following presents how the overlay design for this example is affected by changing two of these variables: design life and load transfer.

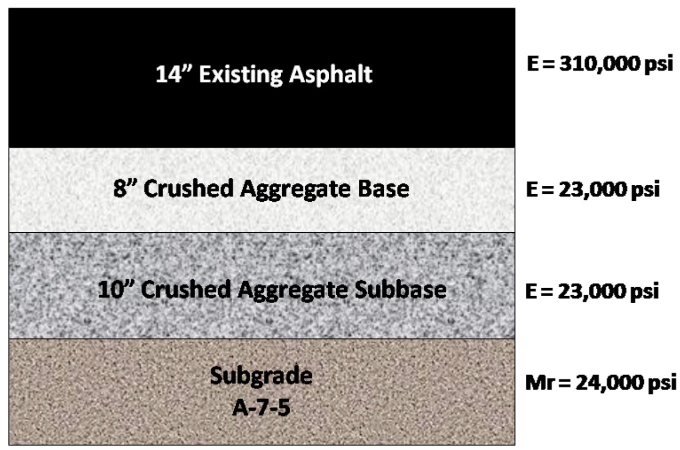

Figure 39. Summary of Existing Pavement Cross-Section.

Table 15. Summary of Design Inputs for D_f.

Input (Units)	Calculations/Estimates	Value
Effective static k-value, psi/in.	Effective dynamic k-value (from deflection testing) / 2 = 1000 / 2	500
E, Concrete elastic modulus, psi	For proposed overlay: estimated from project mix designs and specifications	4,800,000
S'_c, Concrete modulus of rupture, psi		650
J, Load transfer factor	Based on Table 2.6 in Part II (pp. II-26) of the 1993 AASHTO Guide for a JPCP overlay with dowels and asphalt shoulders	3.2
C_d, Drainage coefficient	Typically 1.0 for poor subdrainage conditions	1.0
Δp, Design serviceability loss	(Initial Serviceability: 4.5) – (Terminal Serviceability: 2.5)	2
R, Reliability (%)	Typical value for high-traffic concrete overlay	95
S_o, Standard deviation	Typical value for high-traffic concrete overlay	0.39
W_{18}, Future traffic (ESALs)	ESAL calculations according to local/regional load equivalency factors	13,000,000

Effect of Changing Design Life

If the overlay design life is changed from 30 to 20 years, the ESALs decrease from 13,000,000 to 7,920,000. This decrease changes the required slab thickness (D_f), and in this case the required overlay thickness (D_{ol}), in Step 1 from 10.5 to 9.7 in. The change in design life decreases the required overlay thickness by 0.5 in. (with rounded thicknesses changing from 10.5 to 10.0 in.).

Effect of Changing Load Transfer

If, instead of asphalt shoulders, tied concrete shoulders are used to improve the load transfer efficiency of the unbonded overlay, the load transfer coefficient, J, would change from 3.2 to 2.8 based on table 2.6 in Part II of the 1993 AASHTO Guide. This decrease changes the required slab thickness (D_f), and in this case the required overlay thickness (D_{ol}), in Step 1 from 10.5 to 9.7 in. The change in load transfer coefficient, J, will decrease the required overlay thickness by approximately 0.5 in. (with rounded thicknesses changing from 10.5 to 10.0 in.).

5.5.4. AASHTO Pavement ME Design Guide

The design process for designing unbonded overlays of asphalt pavements follows guidelines similar to those for designing a new concrete pavement, where the existing pavement is treated as the base. The traffic and climate inputs are the same as those described above for the design of bonded overlays in Section 5.1, Bonded Overlay over Existing Concrete Pavement. The main differences are the JPCP Design Properties inputs described in Step 5 and the Pavement Structure inputs described in Step 6 below.

Step 1. Input General Information and Performance Criteria

For this example, the following inputs are entered into the General Information menu:

- Design type: Overlay.
- Pavement type: JPCP over AC.
- Design life: 30 years.
- Estimated construction date for the existing pavement: August 1955.
- Estimated construction date for the proposed overlay: September 2011.
- Expected date for overlay opening to traffic: October 2011.

Next, performance criteria for the proposed overlay are defined. In this case, AASHTOWare Pavement ME Design default thresholds are used for smoothness/terminal IRI (172 in./mile), transverse cracking (15%), and faulting (0.12 in.). The reliability is also specified for each performance indicator; in this case, 95% is used.

Step 2. Input Traffic Data

For this example, the following general traffic inputs are entered:

- Initial 2-way AADTT: 1,350.
- Number of lanes: 2 lanes each direction.
- Directional distribution factor (%): 50.
- Lane distribution factor (%): 85.
- Operational speed (mph): 60.

AASHTOWare Pavement ME Design default values (Level 3) based on nationally developed distributions from the LTPP database are used for the following traffic inputs (load spectra):

- Traffic volume adjustment factors:
    - Vehicle class distribution.*
        - Traffic growth.**
    - Monthly vehicle distribution.
    - Hourly truck distribution.
- Axle load distribution.
- General traffic inputs (axle configuration, lateral wander, and wheelbase).

*For the vehicle class distribution, the road functional classification is selected as Principal Arterials (Interstate and Defense), and the TTC group is selected to be TTC13 for a major mixed truck route.

** For the traffic growth, a rate of 2.3% (linear growth) is entered.

Step 3. Input Climate Data

The location for this example is in Wichita, Kansas. The main Climate screen is used to do the following:

- Generate a new climatic data file. For this example, climatic data were selected from the Wichita Mid-Continent Airport weather station.
- Enter the annual average water table depth: 12 ft.

Step 4. Input Asphalt Layer Properties

This screen is used to enter the general pavement condition of the existing asphalt layer. In this example, the pavement condition rating of "Poor" is used because stripping and debonding of the upper asphalt layers was observed throughout the section.

Step 5. Input JPCP Design Properties

Figure 40 shows a screen capture of the JPCP Design Properties menu. For unbonded overlays of asphalt pavement, the

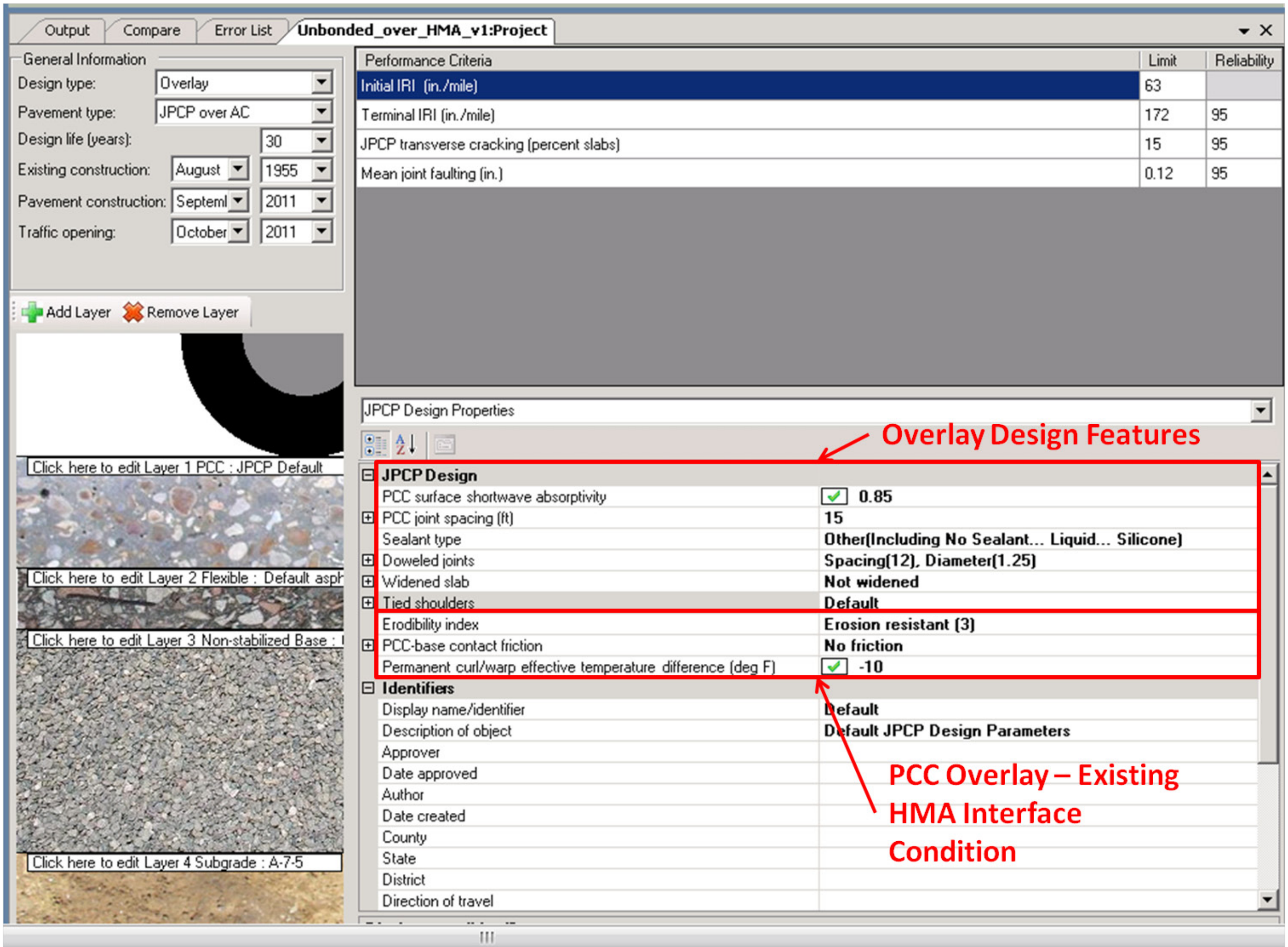

Figure 40. Screen Capture of AASHTOWare Pavement ME Design JPCP Design Properties Menu.

inputs entered correspond to the proposed unbonded overlay: transverse joint spacing and dowel bar reinforcement diameter and spacing. Dowels (1.25 in. diameter) spaced at 12 in. are included for load transfer in the first iteration of this example.

Also in the JPCP Design Properties menu, the interface condition that exists between the bottom of the overlay and the surface of the base (existing asphalt pavement) is defined. In this case, "No friction" is used to indicate that the two layers are unbonded. It is assumed that the bond between the two layers will weaken quickly after construction due to traffic and moisture. The erodibility of the base layer must also be selected.

Step 6. Input Pavement Structural Layers

The Pavement Structure menu is used to define the pavement system layers and enter each layer's material properties. The specific material inputs for each layer are described below.

Overlay Layer Properties

The proposed overlay layer is defined in terms of general (PCC), thermal, mix, shrinkage, and strength properties. A thickness of 9 in. is used for the first overlay trial design. Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.20) and unit weight (150 pcf). Default values in AASHTOWare Pavement ME Design are used for the thermal properties, except for CTE (5.5×10^{-6}/°F). Inputs for mix properties are project specific and are obtained from mix designs and specifications. These inputs include cement type (Type I) and cementitious content (550 lb/yd^3), water/cement ratio (0.42), and aggregate type (limestone). Level 3 inputs are used for the strength properties of the proposed overlay, in this case a modulus of rupture of 650 psi.

Existing Asphalt Pavement Layer Properties

Similarly, this menu is used to define the existing asphalt layer in terms of asphalt mix volumetrics and mechanical and thermal properties. A thickness of 5 in. is used for the asphalt layer thickness after milling because this project consists of milling and inlaying to maintain the existing profile elevations.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	140.16	95.00	99.61	Pass
Mean joint faulting (in.)	0.12	0.09	95.00	99.73	Pass
JPCP transverse cracking (percent slabs)	15.00	12.03	95.00	98.46	Pass

Figure 41. AASHTOWare Pavement ME Design Distress Prediction Summary for 9 in. Unbonded Overlay with Dowels.

Level 3 values for the remaining inputs on this screen are obtained from the typical mixture properties used by each local agency.

Base and Subgrade Materials Layer Properties

The Pavement Structure menu is also used to define the base and subgrade materials. For this example, the base and subbase were combined into one layer 18 in. thick, as was done for the modulus backcalculation. Default/typical values for crushed gravel materials are used for the rest of the inputs.

For the subgrade soils, Level 3 inputs are used, including the soil classification from the soil survey (A-7-5) and the estimated subgrade resilient modulus (8,400 psi). Note that the backcalculated subgrade resilient modulus (24,000 psi) is multiplied by 0.35 to adjust to a laboratory resilient modulus, which is the corresponding input to AASHTOWare Pavement ME Design.

Step 7. Run Analysis and Evaluate Results

At this point, the AASHTOWare Pavement ME Design analysis is run, and the results predict that an overlay 9 in. thick with 15 ft joint spacing and dowels will perform satisfactorily in terms of smoothness, faulting, and percent slabs cracked. Figure 41 summarizes the performance predictions at the specified reliability of 95% for this run.

Figure 42 through figure 44 show the AASHTOWare Pavement ME Design predicted faulting, cracking, and IRI plots.

5.5.5. AASHTO Pavement ME Design Guide: Critical Design Variables

Effect of Changing Design Life

If the overlay design life is changed from 30 to 20 years, the required overlay thickness decreases from 9 in. to 8.5 in., which is a result of 10 fewer years of traffic and climate effects. The change in thickness is 0.5 in.

Effect of Changing Load Transfer

If, instead of asphalt shoulders, tied concrete shoulders are used to improve the load transfer efficiency of the unbonded overlay,

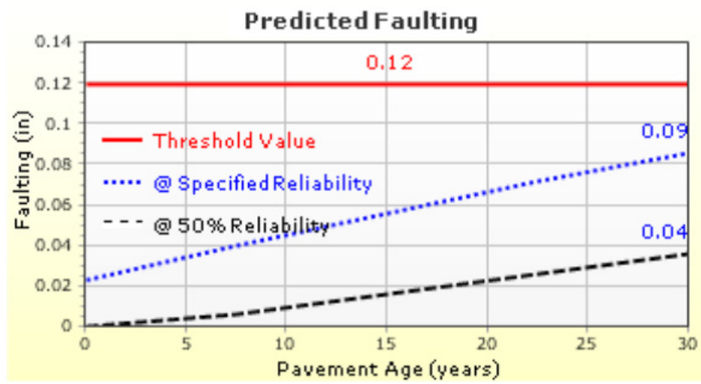

Figure 42. AASHTOWare Pavement ME Design Predicted Faulting Plot for 9 in. Unbonded Overlay with Dowels.

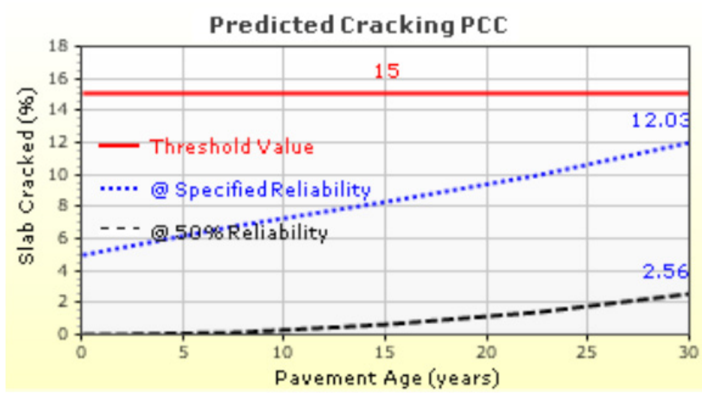

Figure 43. AASHTOWare Pavement ME Design Predicted Cracking Plot for 9 in. Unbonded Overlay with Dowels.

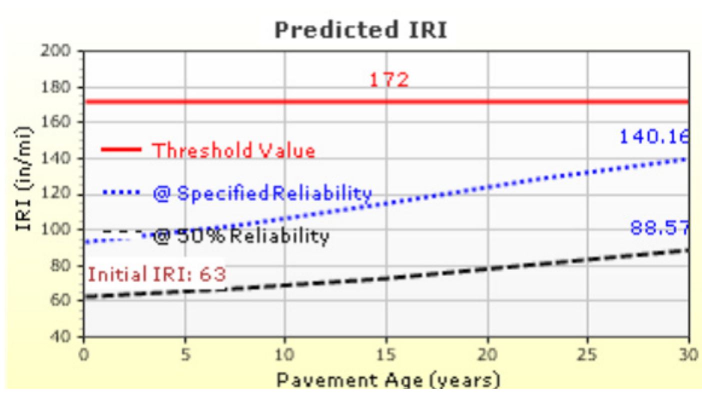

Figure 44. AASHTOWare Pavement ME Design Predicted IRI Plot for 9 in. Unbonded Overlay with Dowels.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	127.08	95.00	99.94	Pass
Mean joint faulting (in.)	0.12	0.07	95.00	99.99	Pass
JPCP transverse cracking (percent slabs)	15.00	14.70	95.00	95.46	Pass

Figure 45. AASHTOWare Pavement ME Design Distress Prediction Summary for 20-year Design Life and 8.5 in. Overlay with Dowels.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	132.99	95.00	99.85	Pass
Mean joint faulting (in.)	0.12	0.07	95.00	99.98	Pass
JPCP transverse cracking (percent slabs)	15.00	13.86	95.00	96.63	Pass

Figure 46. AASHTOWare Pavement ME Design Distress Prediction Summary for 8.0 in. Overlay with Dowels and Tied PCC Shoulders.

Table 16. Summary of Results.

Method	Scenario	Thickness(in.)
1993 AASHTO Guide	Original scenario	10.5
	Changing design life (from 30 to 20 years)	10.0
	Changing load transfer coefficient (from asphalt shoulders to concrete tied shoulders)	10.0
AASHTO Pavement ME Design Guide	Original scenario	9.0
	Changing design life (from 30 to 20 years)	8.5
	Changing load transfer coefficient (from asphalt shoulders to concrete tied shoulders)	8.0

the required overlay thickness decreases from 9 in. to 8 in. The change in thickness is 1 in.

5.5.6. Summary of Results

A JPCP overlay 10.5 in. thick with dowels and asphalt shoulders was determined for this example using the 1993 AASHTO Guide. An overlay 9 in. thick with 15 ft joint spacing, dowels, and asphalt shoulders was determined using the AASHTO Pavement ME Design Guide. At this point in the overlay design process, the next steps would be to conduct mix designs and assemble surface preparation specifications.

5.6. Unbonded Overlay over Existing Composite Pavement (CRCP)

5.6.1. Scenario

A CRCP along a rural Interstate originally built in 1969 is scheduled for rehabilitation. This section received an asphalt overlay in 1990. The composite pavement structure consists of 4 in. of asphalt over the original 7 in. thick CRCP on compacted subgrade. Lanes are 12 ft wide, with 10 ft wide asphalt shoulders. A detailed pavement evaluation revealed that the existing concrete is in fair to poor condition and, as a result, an unbonded concrete overlay is being considered for rehabilitation purposes. In order to effectively design the unbonded overlay, the following design information has been gathered:

Historical Records

- Soil survey indicates that subgrade materials consist mainly of clayey soils (A-6).

Deflection Testing Results

- Backcalculated E (psi) for asphalt and concrete: 200,000 and 3,000,000, respectively.
- Backcalculated Subgrade Modulus, Mr (psi): 40,000. Note that for the subgrade resilient modulus (Mr) input to

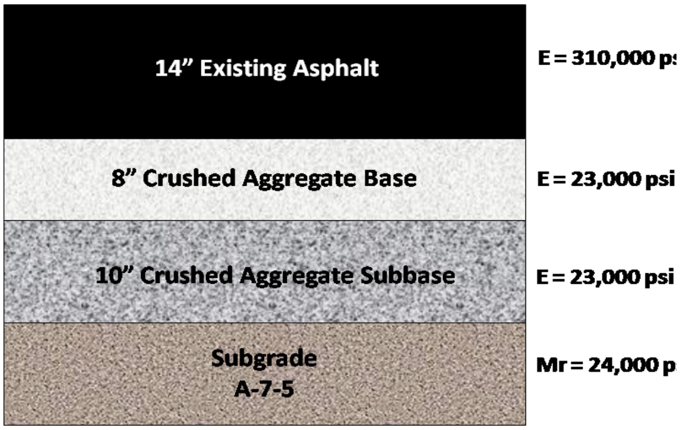

Figure 47. Summary of Existing Pavement Cross-Section.

AASHTOWare Pavement ME Design, the backcalculated value is adjusted to represent laboratory conditions. In this case, 0.35*backcalculated Mr (psi): 14,000.

- Effective dynamic k-value (psi/in.): 1,000.

Distress Survey Results

- Estimated number of unrepaired spalling areas and deteriorated transverse cracks: 200 per mile.
- Moderate transverse and longitudinal reflective cracking ("D" cracking distresses reflecting through asphalt overlay); a specification to mill 2 in. of the existing asphalt before the overlay is applied.

Traffic

- Future ESALs (20-year design life): 24,000,000.
- Initial 2-way AADTT: 3,220; Growth rate: 2.5% (linear).
- Existing roadway: 4 lanes (2 lanes each way).
- Directional distribution: 50%; Design lane distribution factor: 90%.

Climate

- Location: Peoria, Illinois.
- Annual average water table depth: 6 ft.

Proposed Overlay

- E (psi) for concrete: 4,800,000.
- 28-day flexural strength (psi): 650.
- CTE (10^{-6}/°F): 5.5.

The following sections illustrate how to perform the overlay design for this example using both the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide.

Table 17. Summary of Design Inputs for D_f.

Input (Units)	Calculations/Estimates	Value
Effective static k-value, psi/in.	Effective dynamic k-value (from deflection testing) / 2 = 1000 / 2	500
E, Concrete elastic modulus, psi	For proposed overlay: estimated from project mix designs and specifications	4,800,000
S'_c, Concrete modulus of rupture, psi		650
J, Load transfer factor	Based on Table 2.6 in Part II of the 1993 AASHTO Guide, for a CRCP with asphalt shoulders	2.9
C_d, Drainage coefficient	Typically 1.0 for poor subdrainage conditions	1.0
Δp, Design serviceability loss	(Initial Serviceability: 4.5) – (Terminal Serviceability: 2.5)	2
R, Reliability (%)	Typical value for high-traffic concrete overlay	95
S_o, Standard deviation	Typical value for high-traffic concrete overlay	0.39
W_{18}, Future traffic (ESALs)	ESAL calculations according to local/ regional load equivalency factors	24,000,000

5.6.2. 1993 AASHTO Guide

The design of unbonded overlays over existing composite pavements using the 1993 AASHTO Guide follows the steps described above in Section 5.4, Unbonded Overlay over Existing Concrete Pavement. The design process is based on the following equation:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})}$$

Where, D_{ol} = required concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

Step 1. Determine D_f

Determine D_f using the rigid pavement design equation or nomograph in figure 3.7 in Part II (pp. II-45) of the 1993 AASHTO Guide. Table 9 summarizes the inputs used to determine D_f. Use of the nomograph yields a required slab thickness (D_f) of 11.1 in.

Step 2. Determine D_{eff}

Determine D_{eff} using the Condition Survey method. The Remaining Life method is not applicable to composite pavements.

Condition Survey Method

Based on the distress survey results, determine the adjustment factor for use in the following equation:

$$D_{eff} = F_{jcu} * D$$

Where, D = existing slab thickness (in.), 7 in., F_{jcu} = joint and cracks adjustment factor for unbonded overlays, 0.90

- Determined using figure 5.13 in Part III of the 1993 AASHTO Guide (see figure 16 below) and the total number of unrepaired spalling areas, deteriorated joints, and cracks per mile, which in this case is 200.

Note that for composite pavements the asphalt layer is neglected when determining D_{eff}.

Therefore, the effective thickness of the existing concrete slab calculated with this method is

$$D_{eff} = F_{jcu} * D = 0.90 * 7 = 6.30 \text{ in.}$$

Step 3. Compute D_{ol}

Compute the required concrete overlay thickness using the 1993 AASHTO Guide equation for unbonded overlays over existing concrete pavements:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(11.1^2 - 6.30^2)} = 9.14 \text{ in.}$$

An overlay thickness of 9.5 in. can be used for this example. Additional design features are discussed below in Section 5.6.6, Summary of Results.

5.6.3. 1993 AASHTO Guide: Critical Design Variables

The most sensitive variables for this method when designing unbonded overlays over composite pavements include traffic, load transfer coefficient, drainage coefficient, modulus of rupture, k-value, and serviceability loss. Presented below are ways the overlay design for this example is affected by changing two of these variables: design life and k-value.

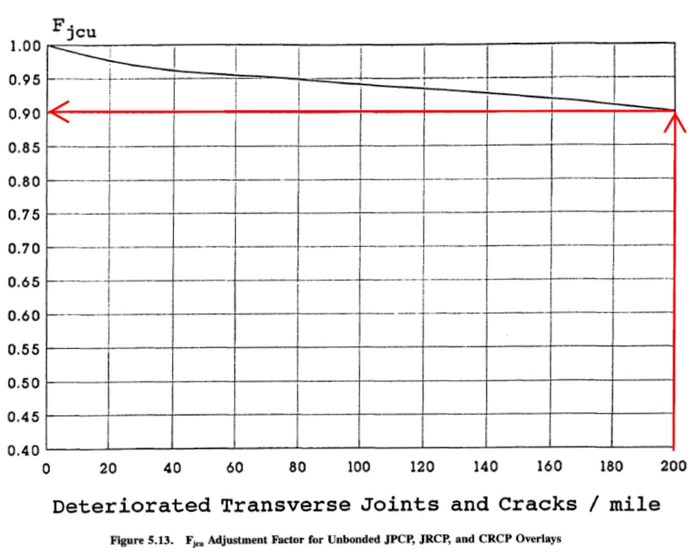

Figure 48. Figure 5.13 from Part III of the 1993 AASHTO Guide Used to Determine F_{jcu} for Unbonded Overlays.

Effect of Changing Design Life

If the overlay design life were changed from 20 to 40 years, the ESALs would decrease from 24,000,000 to 81,322,000. This decrease changes the required slab thickness (D_f) in Step 1 from 11.1 to 13.4 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(13.4^2 - 6.30^2)} = 11.83 \text{ in.}$$

The change in design life from 20 to 40 years increases the required overlay thickness by approximately 2.5 in., (with rounded thicknesses changing from 9.5 to 12.0 in.).

Effect of Changing k-value

If the dynamic modulus of subgrade reaction is changed from 1,000 to 500 psi/in., the required slab thickness (D_f) in Step 1 changes from 11.1 to 11.5 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(11.5^2 - 6.30^2)} = 9.62 \text{ in.}$$

The change in k-value increases the required overlay thickness by approximately 0.5 in., (with rounded thicknesses changing from 9.5 to 10.0 in.).

5.6.4. AASHTO Pavement ME Design Guide

The design process for unbonded overlays of concrete or composite pavements follows the general steps for using AASHTOWare Pavement ME Design described above in Section 5.4, Unbonded Overlay over Existing Concrete Pavement.

Step 1. Input General Information and Performance Criteria

For this example, the following inputs are entered to the General Information menu:

- Design type: Overlay.
- Pavement type: CRCP over CRCP – Unbonded.
- Design life: 20 years.
- Estimated construction date for the existing pavement: August 1969.
- Estimated construction date for the proposed overlay: September 2011.
- Expected date for overlay opening to traffic: October 2011.

Next, the Performance Criteria menu inputs for the proposed overlay are defined. In this case, the AASHTOWare Pavement ME Design default thresholds are used for the following: smoothness (172 in./mi) and punchouts (10/mile).

Step 2. Input Traffic Data

For this example, the following general traffic inputs are entered:

- Initial 2-way AADTT: 3,220.
- Number of lanes: 2 lanes each direction.
- Directional distribution factor (%): 50.
- Lane distribution factor (%): 100.
- Operational speed (mph): 60.

AASHTOWare Pavement ME Design default values (Level 3) based on nationally developed distributions from the LTPP database are used for the following traffic inputs (load spectra):

- Traffic volume adjustment factors:
  - Vehicle class distribution.*
    - Traffic growth.**
  - Monthly vehicle distribution.
  - Hourly truck distribution.
- Axle load distribution.
- General traffic inputs (axle configuration, lateral wander, and wheelbase).

*For the vehicle classification distribution, the road functional classification is selected to be Principal Arterials (Interstate and Defense), and the TTC group is selected to be TTC5 for a major single- and multi-trailer route.

** For the traffic growth, a rate of 2.5% (linear growth) is entered.

Step 3. Input Climate Data

The location for this example is in Peoria, Illinois. The main Climate screen is used to do the following:

- Create a new climatic data file. For this example climatic data from the Greater Peoria Regional Airport weather station were used.
- Enter the annual average water table depth: 6 ft.

Step 4. Input CRCP Design Properties

Figure 49 shows a screen capture of the CRCP Design Properties menu, where the inputs entered correspond to

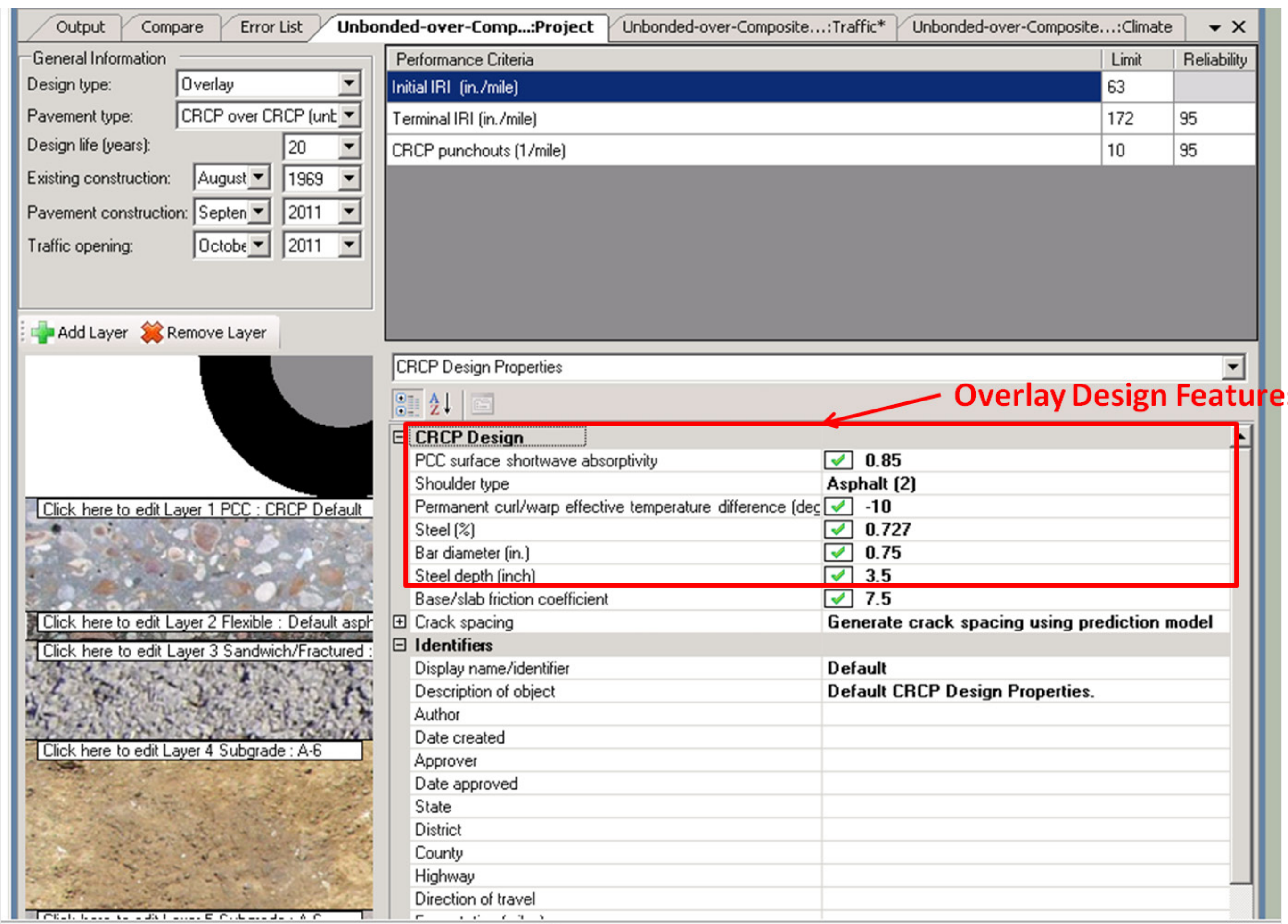

Figure 49. Screen Capture of AASHTOWare Pavement ME Design CRCP Design Properties Menu.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	130.88	95.00	99.95	Pass
CRCP punchouts (1/mile)	10.00	8.04	95.00	98.21	Pass

Figure 50. AASHTOWare Pavement ME Design Distress Prediction Summary for 8.0 in. CRCP Unbonded Overlay.

the shoulder type and steel reinforcement. In this case, the Illinois Department of Transportation (IDOT) standard detail specifies the following for CRCP from 7.75 to 8.5 in. in thickness: #6 bars spaced at 7 5/8 in. (based on 19 bars per lane) for the longitudinal steel, and #4 bars spaced at 48 in. for the transverse steel, which is not a required input. The depth to steel bar reinforcement for this example is 3.5 in. Default values in AASHTOWare Pavement ME Design are used for the remaining inputs on this screen.

Step 5. Input Foundation Support

The Foundation Support menu provides the option to have AASHTOWare Pavement ME Design estimate the modulus of subgrade reaction (default) or to have the user enter it manually. Note that if a value is to be entered manually, AASHTOWare Pavement ME Design requires the dynamic k-value, which is determined through deflection testing and backcalculation. In this example, the option to have AASHTOWare Pavement ME Design calculate the modulus of subgrade reaction is used.

Step 6. Input Pavement Structural Layers

The Pavement Structure menu is used to define the pavement system layers and each layer's material properties. The specific material inputs for each layer are described below.

Overlay Layer Properties

The Pavement Structure menu is used to define the overlay layer in terms of general (PCC), thermal, mix, shrinkage, and strength properties. A thickness of 8.0 in. is used for the first overlay trial design. Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.2) and unit weight (150 pcf). Default values in AASHTOWare Pavement ME Design are used for the thermal properties, except for CTE (5.5x10^{-6}/°F)).

Inputs for mix properties are project specific and are obtained from mix designs and specifications. These include cement type (Type I) and content (550 lb/yd^3), water/cement ratio (0.42), and aggregate type (limestone). For this example, Level 3 inputs are used for the proposed overlay strength properties, with a modulus of rupture of 650 psi.

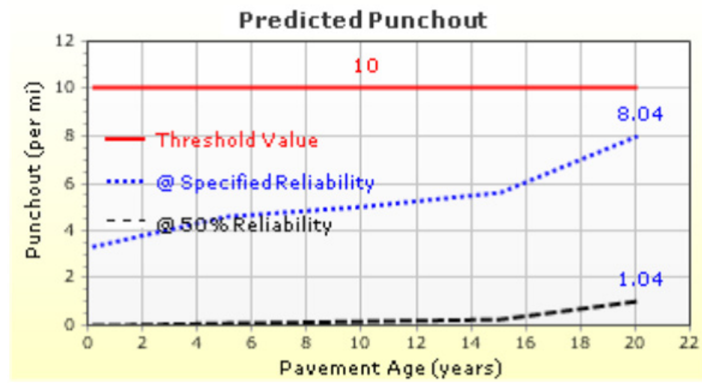

Figure 51. AASHTOWare Pavement ME Design Predicted Punchouts Plot for 8.0 in. Unbonded CRCP Overlay.

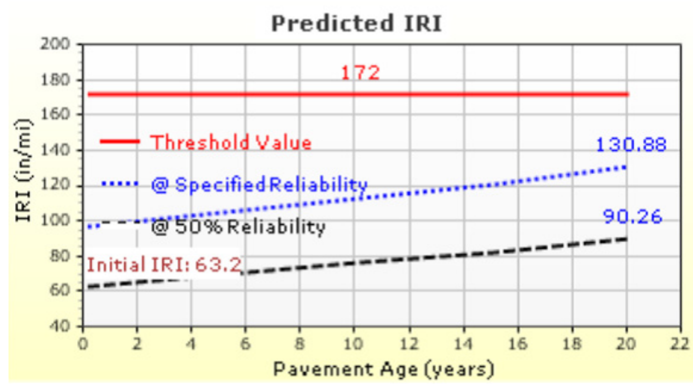

Figure 52. AASHTOWare Pavement ME Design Predicted IRI Plot for 8.0 in. Unbonded CRCP Overlay.

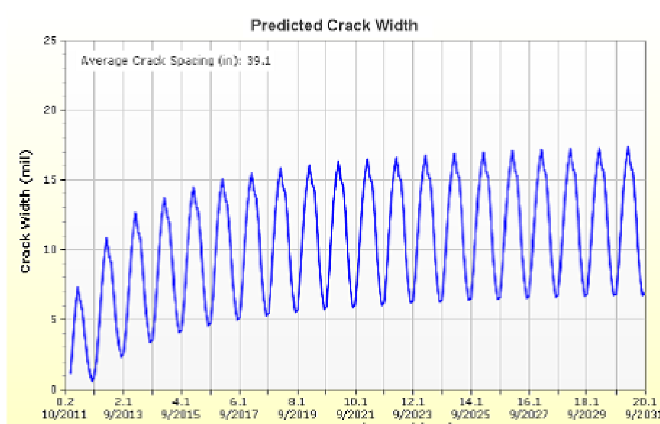

Figure 53. AASHTOWare Pavement ME Design Predicted Crack Width Plot for 8.0 in. Unbonded CRCP Overlay.

Asphalt Layer

The existing asphalt layer is typically used as the interlayer with the proposed concrete overlay. In this case, milling of the top 2 in. of the existing asphalt layer is specified, which leaves 2 in. in place. Level 3 inputs are used to define this layer in terms of asphalt mix volumetrics and mechanical and thermal properties. These inputs are obtained from the typical mixture properties used by the local agency.

Existing CRCP Layer

The existing CRCP is defined in terms of thickness (7 in.), Poisson's ratio (0.2), elastic modulus (3,000,000 psi), and thermal properties.

Subgrade Materials Layer Properties

The Pavement Structure menu is also used to define the subgrade material. Level 3 inputs for the subgrade soils include the soil classification from the soil survey (A-6) and the subgrade resilient modulus (14,000 psi). Note that the backcalculated subgrade resilient modulus (40,000 psi) is multiplied by 0.35 to adjust to a laboratory resilient modulus, which is the corresponding input to AASHTOWare Pavement ME Design.

Step 5. Evaluate Results

At this point, the AASHTOWare Pavement ME Design analysis is run. The results predict that a CRCP overlay with an 8.0 in. thickness and asphalt shoulders will perform satisfactorily in terms of punchouts and smoothness. Figure 50 shows the summary of performance predictions at the specified reliability of 95% for this trial. Figure 51 and Figure 52 show the AASHTOWare Pavement ME Design predicted punchouts and IRI plots.

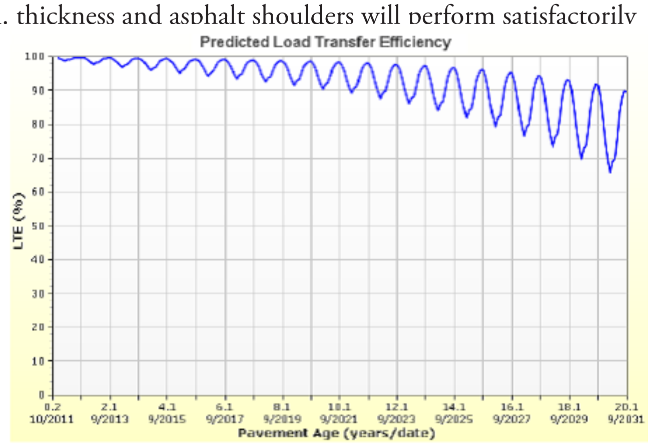

Figure 54. AASHTOWare Pavement ME Design Predicted LTE Plot for 8.0 in. Unbonded CRCP Overlay.

Additional predictions in AASHTOWare Pavement ME Design include crack width and crack load transfer efficiency (LTE). Figure 53 and figure 54 show the predicted crack width and LTE plots. The average crack spacing calculated for this design is 39.1 in.

5.6.5. AASHTO Pavement ME Design Guide: Critical Design Variables

Effect of Changing Design Life

If the overlay design life is changed from 20 to 40 years, the required overlay thickness needs to be increased from 8.0 in. to 10.0 in. (change in thickness: 2 in.). Figure 55 shows the summary of results for this trial.

Effect of Changing PCC Zero-Stress Temperature

The PCC zero-stress temperature represents the temperature at which the concrete hardens sufficiently to develop tensile stresses. At this point, the cracks in the CRCP open when the concrete temperature drops below the PCC zero-stress temperature. Paving during the summer months results in high zero-stress temperatures and wider crack openings when the temperature drops.

The PCC zero-stress temperature can be input directly into AASHTOWare Pavement ME Design, or AASHTOWare Pavement ME Design can estimate the value based on the construction month selected in Step 1. Section 3.4.3.7 in the M-E PDG manual (NCHRP 2004) explains that this estimate is based on daytime construction with curing compound and does not account for the effect of mineral and chemical admixtures.

The original scenario for this example involved construction during the month of September (See Step 1). This results in a PCC zero-stress temperature prediction of 94°F. If the construction month is changed to June, the PCC zero-stress temperature prediction changes to 100.4° F. With this change,

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	155.56	95.00	98.92	Pass
CRCP punchouts (1/mile)	10.00	5.90	95.00	99.79	Pass

Figure 55. AASHTOWare Pavement ME Design Distress Prediction Summary for 40-year Design Life and 10.0 in.CRCP Overlay.

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	126.85	95.00	99.98	Pass
CRCP punchouts (1/mile)	10.00	6.28	95.00	99.64	Pass

Figure 56. AASHTOWare Pavement ME Design Distress Prediction Summary for 100.4°F "PCC Zero-Stress Temperature" and 8.5 in. CRCP Overlay.

the required overlay thickness needs to be increased from 8.0 in. to 8.5 in. (change in thickness: 0.5 in.).

NOTE: For CRCP overlay designs, the current version of AASHTOWare Pavement ME Design (DARWin-ME 1.1.32) is not reporting the PCC zero-stress temperature correctly. However, the change in the month of construction is reflected in the predicted punchouts. Also, the direct input of the PCC zero-stress temperature is not working. It is anticipated that these issues will be fixed in the next software release.

5.6.6. Summary of Results

A CRCP overlay 9.5 in. thick with asphalt shoulders was determined for this example using the 1993 AASHTO Guide. An overlay 8.0 in. thick with asphalt shoulders was determined using the AASHTO Pavement ME Design Guide. The steel design for the unbonded CRCP overlay is designed in accordance with local agency standard cross-sections. In this case, the IDOT standard indicates the following for an 8.0 in. pavement thickness: 0.75 in. diameter (#6) bars spaced at 7 5/8 in. for the longitudinal steel, and 0.5 in. diameter (#4) bars spaced at 48 in. for the transverse steel. At this point in the overlay design process, the next steps are conducting mix designs and assembling surface preparation specifications.

Table 18. Summary of Results.

Method	Scenario	Thickness(in.)
1993 AASHTO Guide	Original scenario	9.5
	Changing design life (from 20 to 40 years)	12.0
	Changing composite dynamic k-value (from 1000 to 500 psi/in))	10.0
AASHTO Pavement ME Design Guide	Original scenario	8.0
	Changing design life (from 20 to 40 years)	10.0
	Changing "PCC zero-stress temperature" (by changing construction month from September [94°F] to June [100.4°F])	8.5

5.7. Unbonded Overlay over Existing Composite Pavement (JPCP)

5.7.1. Scenario

A JPCP along an urban Interstate originally built in 1970 is scheduled for rehabilitation. This section has received different asphalt overlays, and the composite pavement structure consists of 5 in. of asphalt over the original 9 in. thick JPCP over 12 in. of aggregate base on natural subgrade (see figure 57). Lanes are 12 ft wide, with 10 ft wide concrete shoulders. A detailed pavement evaluation revealed that the existing concrete is in fair to poor condition and, as a result, an unbonded concrete overlay is being considered for rehabilitation purposes. In order to effectively design the unbonded overlay, the following design information has been gathered:

Historical Records

- Soil survey indicates that subgrade materials consist mainly of clayey soils (A-6).

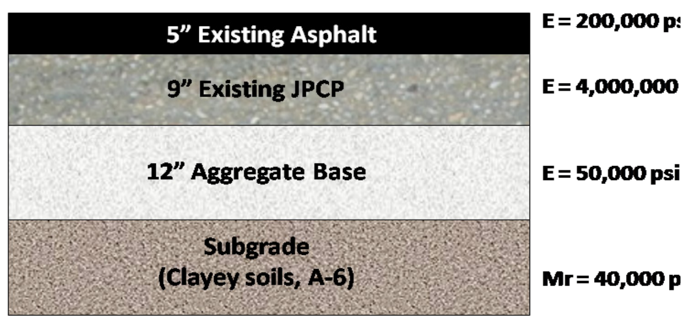

Figure 57. Summary of Existing Pavement Cross-Section.

Deflection Testing Results

- Backcalculated elastic modulus, E (psi) for asphalt, concrete, and base: 200,000, 4,000,000, 50,000, respectively
- Back-calculated subgrade modulus, Mr (psi): 40,000.

Note that for the subgrade resilient modulus (Mr) input to AASHTOWare Pavement ME Design, the backcalculated value is adjusted to represent laboratory conditions. In this case, 0.35*backcalculated Mr (psi): 14,000.

- Effective dynamic k-value (psi/in.): 1,000.

Distress Survey Results

- Estimated number of unrepaired spalling areas, deteriorated transverse joints, and cracks: 120 per mile.

- Moderate transverse and longitudinal reflective cracking; a specification to mill 2 in. of the existing asphalt before the overlay is applied.

Traffic

- Future ESALs (20-year design life): 56,283,000.
- Initial 2-way AADTT: 8,000; Growth rate: 2.0% (compound growth).
- Existing roadway: 4 lanes (2 lanes each way).
- Directional distribution: 50%, Design lane distribution factor: 85%.

Climate

- Location: Atlanta, Georgia.
- Annual average water table depth: 6 ft.

Proposed Overlay

- E (psi) for concrete: 4,800,000.
- 28-day flexural strength (psi): 650.
- CTE (10^{-6}/°F): 5.5.
- Joint spacing: 15 ft.
- 1.25 in. dowels spaced at 12 in.
- Tied PCC shoulders.

The following sections illustrate how to perform the overlay design for this example using both the 1993 AASHTO Guide and the AASHTO Pavement ME Design Guide.

5.7.2. 1993 AASHTO Guide

The design of unbonded overlays over existing composite pavements using the 1993 AASHTO Guide follows the steps described above in Section 5.4, Unbonded Overlay over Existing Concrete Pavement. The design process is based on the following equation:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})}$$

Where: D_{ol} = required jointed plain concrete overlay thickness (in.), D_f = slab thickness required to carry the future traffic (in.), and D_{eff} = effective thickness of the existing concrete slab (in.).

Step 1. Determine D_f

Determine D_f using the rigid pavement design equation or nomograph in figure 3.7 in Part II (pg. II-45) of the 1993 AASHTO Guide. Table 19 summarizes the inputs used to determine D_f. Use of the nomograph yields a required slab thickness (D_f) of 12.4 in.

Step 2. Determine D_{eff}

Determine D_{eff} using the Condition Survey method. The Remaining Life method is not applicable to composite pavements.

Condition Survey Method

Based on the distress survey results, determine the adjustment factor for use in the following equation:

$$D_{eff} = F_{jcu} * D$$

Where, D = existing slab thickness (in.), 9 in., F_{jcu} = joint and cracks adjustment factor for unbonded overlays, 0.93

Table 19. Summary of Design Inputs for D_f.

Input (Units)	Calculations/Estimates	Value
Effective static k-value, psi/in.	Effective dynamic k-value (from deflection testing) / 2 = 1000 / 2	500
E, Concrete elastic modulus, psi	For proposed overlay: estimated from project mix designs and specifications	4,800,000
S'_c, Concrete modulus of rupture, psi		650
J, Load transfer factor	Based on Table 2.6 in Part II of the 1993 AASHTO Guide, for a JPCP with dowels and tied concrete shoulders	2.8
C_d, Drainage coefficient	Typically 1.0 for poor subdrainage conditions	1.0
Δp, Design serviceability loss	(Initial Serviceability: 4.5) – (Terminal Serviceability: 2.5)	2
R, Reliability (%)	Typical value for high-traffic concrete overlay	95
S_o, Standard deviation	Typical value for high-traffic concrete overlay	0.39
W_{18}, Future traffic (ESALs)	ESAL calculations according to local/regional load equivalency factors	56,238,000

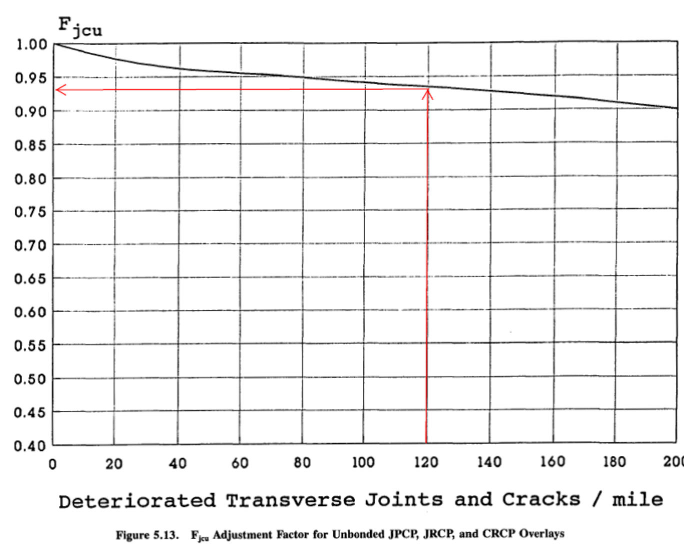

Figure 58. Figure 5.13 from Part III of AASHTO (1993) Guide Used to Determine F_{jcu} for Unbonded Overlays.

- Determined using figure 5.13 in Part III of the 1993 AASHTO Guide (see figure 58) and the total number of unrepaired spalling areas, deteriorated joints, and cracks per mile, which in this case is 120.

Note that for composite pavements, the asphalt layer is neglected when determining D_{eff}.

Therefore, the effective thickness of the existing concrete slab calculated with this method is

$$D_{eff} = F_{jcu} * D = 0.93*9 = 8.37 \text{ in.}$$

Step 3. Compute D_{ol}

Compute the required concrete overlay thickness using the 1993 AASHTO Guide equation for unbonded overlays over existing concrete pavements:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(12.4^2 - 8.37^2)} = 9.15 \text{ in.}$$

An overlay 9.5 in. thick with dowels and tied concrete shoulders may be used for this example. Additional design features are discussed in Section 5.7.6, Summary of Results.

5.7.3. 1993 AASHTO Guide: Critical Design Variables

The most sensitive variables for this method when designing unbonded overlays over composite pavements include traffic, load transfer coefficient, drainage coefficient, modulus of rupture, k-value, and serviceability loss. Presented below are ways the overlay design for this example is affected by changing two of these variables: load transfer coefficient and modulus of rupture.

Effect of Changing Load Transfer Coefficient

If asphalt shoulders were used instead of tied concrete shoulders, the load transfer coefficient would change from 2.8 to 3.2. This increase changes the required slab thickness (D_f) calculated in Step 1 from 12.4 to 13.4 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(13.4^2 - 8.37^2)} = 10.46 \text{ in.}$$

The change in shoulder type (asphalt instead of tied concrete) increases the required overlay thickness by approximately 1 in., from 9.5 to 10.5 in.

Effect of Changing Modulus of Rupture

If the overlay mix design is changed to obtain a higher modulus of rupture , 700 psi, the required slab thickness (D_f) in Step 1 changes from 12.4 to 12.0 in. Repeating Step 3 with the new D_f yields the following:

$$D_{ol} = \sqrt{(D^2_f - D^2_{eff})} = \sqrt{(13.4^2 - 8.37^2)} = 8.60 \text{ in.}$$

The change in flexural strength decreases the required overlay thickness by approximately 0.5 in., from 9.5 to 9.0 in. (rounded overlay thicknesses).

5.7.4. AASHTO Pavement ME Design Guide

The design process for unbonded overlays of concrete or composite pavements follows the general steps for using AASHTOWare Pavement ME Design as described above in Section 5.4, Unbonded Overlay over Existing Concrete Pavement.

Step 1. Input General Information and Performance Criteria

For this example, the following inputs are entered to the General Information menu:

- Design type: Overlay.
- Pavement type: JPCP over JPCP – Unbonded.
- Design life: 20 years.
- Estimated construction date for the existing pavement: May 1970.
- Estimated construction date for the proposed overlay: June 2011.
- Expected date for overlay opening to traffic: August 2011.

Next, Performance Criteria menu inputs for the proposed overlay are defined. In this case, the AASHTOWare Pavement ME Design default thresholds for JPCP are used for smoothness/IRI (172 in./mi), JPCP transverse cracking (% slabs cracked, 15), and mean joint faulting (0.12 in.). The reliability is also specified for each performance indicator; in this case, 95% is used.

Step 2. Input Traffic Data

For this example, the following general traffic inputs are entered:

- Initial 2-way AADTT: 8,000.
- Number of lanes: 2 lanes each direction.
- Directional distribution factor (%): 50.
- Lane distribution factor (%): 85.
- Operational speed (mph): 60.

AASHTOWare Pavement ME Design default values (Level 3) based on nationally developed distributions from the LTPP database are used for the following traffic inputs (load spectra):

Traffic volume adjustment factors:

  - Vehicle class distribution.*
    - Traffic growth.**
  - Monthly vehicle distribution.
  - Hourly truck distribution.
- Axle load distribution.

- General traffic inputs (axle configuration, lateral wander, and wheelbase).

*For the vehicle class distribution, the road functional classification is selected to be Principal Arterials (Interstate and Defense), and the TTC group is selected to be TTC5 for a major single- and multi-trailer route.

** For the traffic growth, a rate of 2.0% (compound growth) is entered.

Step 3. Input Foundation Support

The Foundation Support menu provides the option to have AASHTOWare Pavement ME Design estimate the modulus of subgrade reaction (default) or to have the user enter it manually. Note that if a value is to be entered manually, AASHTOWare Pavement ME Design requires the dynamic k-value, which is determined through deflection testing and backcalculation. In this example, the option to have AASHTOWare Pavement ME Design calculate the modulus of subgrade reaction from the soil resilient modulus is used.

Step 4. Input JPCP Design Features

Figure 59 shows a screen capture of the JPCP Design Features menu, where the inputs entered correspond to the proposed unbonded overlay transverse joint spacing, dowel bar reinforcement diameter and spacing, edge support conditions, and the existing concrete slab-base interface.

A joint spacing of 15 ft is used. Because the example presents a heavy traffic scenario, 1.25 in. dowels spaced at 12 in. and tied concrete shoulders are used for the first trial design. Last in this menu, a “No friction” value is assumed at the interface condition that exists between the bottom of the overlay and the surface of the base (existing JPCP), indicating that the two layers are unbonded.

Step 5. Input Climate Data

The location for this example is in Atlanta, Georgia. The main Climate screen is used to do the following:

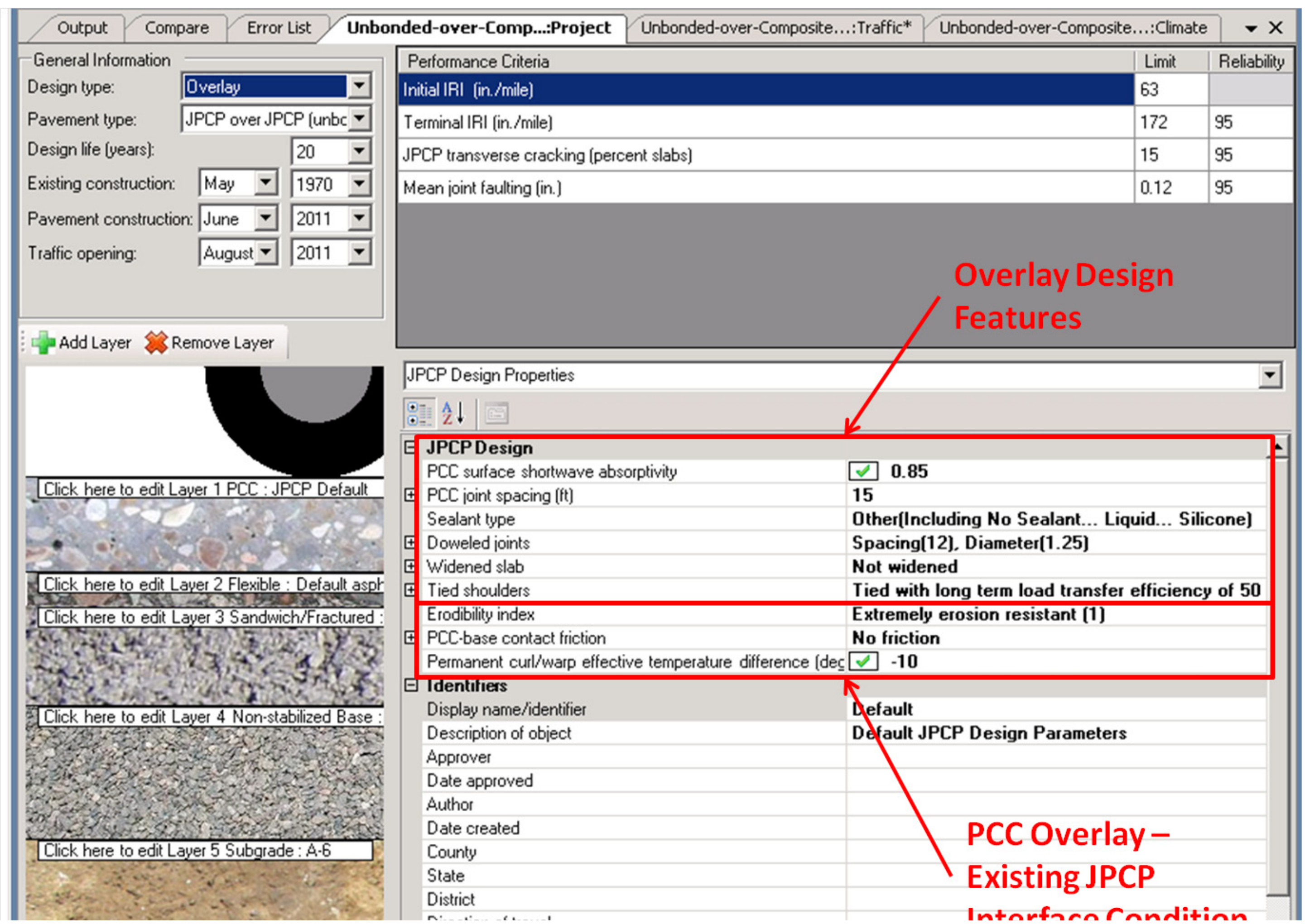

Figure 59. Screen Capture of AASHTOWare Pavement ME Design JPCP Design Properties Menu.

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	126.85	95.00	99.98	Pass
CRCP punchouts (1/mile)	10.00	6.28	95.00	99.64	Pass

Figure 60. AASHTOWare Pavement ME Design Summary of Performance Criteria and Reliability for 8.5 in. Unbonded Overlay with Dowels and Tied Concrete Shoulders.

- Generate a new climatic data file. For this example, climatic data from the Hartsfield-Jackson Atlanta International Airport weather station were used.
- Enter the annual average water table depth: 6 ft.

Step 6. Input Pavement Structural Layers

The Pavement Structure menu is used to define the pavement system layers and each layer's material properties. The specific material inputs for each layer are described below.

Overlay Layer Properties

The overlay layer is defined in terms of general (PCC), thermal, mix, shrinkage, and strength properties. A thickness of 8.5 in. is used for the first overlay trial design. Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.20) and unit weight (150 pcf). Default values in AASHTOWare Pavement ME Design are used for the thermal properties, except for CTE ($5.5x10^{-6}$/°F).

Inputs for mix properties are project specific and are obtained from mix designs and specifications. These include cement type (Type I) and content (600 lb/yd^3), water/cement ratio (0.42), and aggregate type (limestone). For this example, Level 3 inputs are used for the proposed overlay strength properties, with a modulus of rupture of 650 psi.

Asphalt Layer

The existing asphalt layer is typically used as the separator layer with the proposed concrete overlay. In this case, milling of the top 2 in. of the existing asphalt layer is specified, which leaves 3 in. in place. Level 3 inputs are used to define this layer in terms of asphalt mix volumetrics and mechanical and thermal properties. These inputs are obtained from the typical mixture properties used by each local agency.

Existing Concrete Pavement Layer Properties

The existing concrete pavement layer is defined in terms of general, strength, and thermal properties. Typical values for concrete pavements are used for the general properties, such as Poisson's ratio (0.20) and unit weight (150 pcf). In addition, the existing pavement thickness is input (9 in.). For the strength properties, the estimated modulus of elasticity (4,000,000 psi)

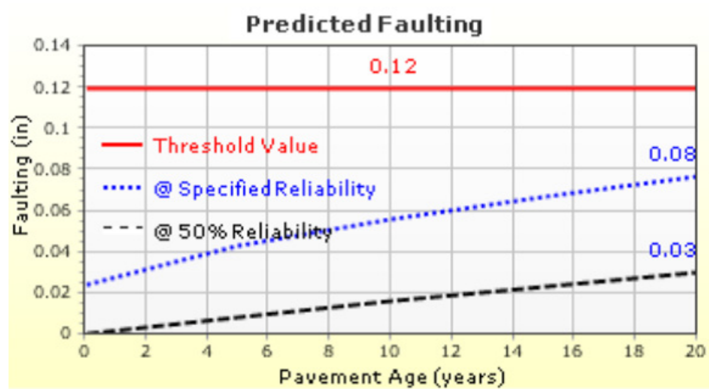

Figure 61. AASHTOWare Pavement ME Design Predicted Faulting Plot for 8.5 in. Unbonded Overlay with Dowels and Tied Concrete Shoulders.

is entered. AASHTOWare Pavement ME Design default values are used for existing concrete thermal properties.

Base and Subgrade Materials Layer Properties

The Pavement Structure menu is also used to define the base and subgrade materials. The inputs for the crushed aggregate base include the backcalculated resilient modulus (50,000 psi) and thickness (12 in.). Default/typical values for crushed gravel materials are used for the rest of the inputs in this example. Level 3 inputs for the subgrade soils include the soil classification from the soil survey (A-6) and the subgrade resilient modulus (14,000 psi). Note that the backcalculated subgrade resilient modulus (40,000 psi) is multiplied by 0.35 to adjust to a laboratory resilient modulus, which is the corresponding input to AASHTOWare Pavement ME Design.

Step 5. Evaluate Results

The AASHTO Pavement ME Design software analysis is now run, and the results predict that an overlay 8.5 in. thick with a 15 ft joint spacing, 1.25 in. dowels , and tied concrete shoulders will meet the performance criteria in terms of smoothness, faulting, and percent slabs cracked. Figure 60 shows the summary of performance predictions at the specified reliability of 95% for this run. Figure 61 through figure 63 show the performance prediction plots for faulting, cracking, and smoothness.

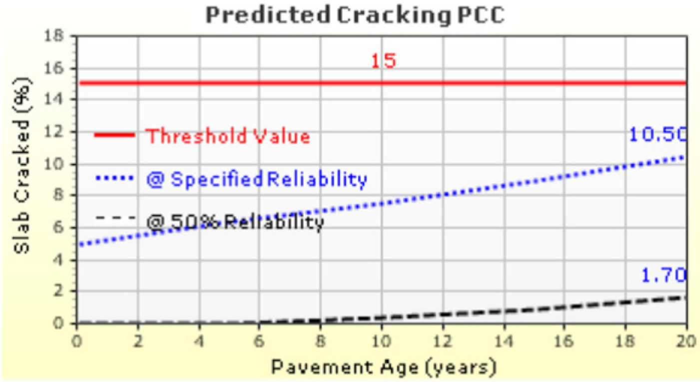

Figure 62. AASHTOWare Pavement ME Design Predicted Cracking Plot for 8.5 in. Unbonded Overlay with Dowels and Tied Concrete Shoulders.

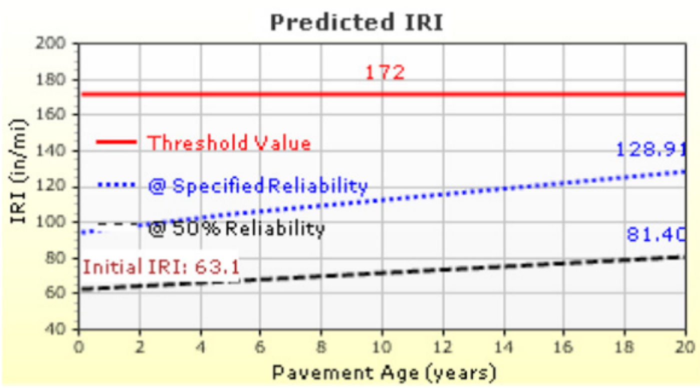

Figure 63. AASHTOWare Pavement ME Design Predicted IRI Plot for 8.5 in. Unbonded Overlay with Dowels and Tied Concrete Shoulders.

5.7.5. AASHTO Pavement ME Design Guide: Critical Design Variables

Effect of Using a Widen Slab and Asphalt Shoulders

If the design lane width is changed by selecting a widened slab in the Design Features menu and entering a 13 ft width, the required overlay thickness may be decreased from 8.5 in. to 7.0 in. (change in thickness: 1.5 in.). Note that, for this trial, the option for tied concrete shoulders was not used, and the use of asphalt shoulders was assumed. In addition, it was assumed that the traffic stripes would be applied, because the lane width was 12 ft, in order to improve edge support by moving the traffic loads away from the slab corners. Figure 64 shows the summary of results for this trial.

Effect of Changing Joint Spacing and Asphalt Shoulders

If the overlay joint spacing for this example is changed from 15 to 12 ft, the required overlay thickness may be decreased from 8.5 in. to 7.5 in. (change in thickness: 1.0 in.). Note that, for this trial, the option for tied concrete shoulders was not used, and the use of asphalt shoulders was assumed. Figure 65 shows the summary of results for this trial.

5.7.6. Summary of Results

A JPCP overlay 9.5 in. thick with dowels and tied concrete shoulders was determined for this example using the 1993 AASHTO Guide. A JPCP overlay 8.5 in. thick with 15 ft joint spacing, 1.25 in. dowels , and tied concrete shoulders was determined using the AASHTO Pavement ME Design Guide. At this point in the overlay design process, the next steps are

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	99.31	95.00	100.00	Pass
Mean joint faulting (in.)	0.12	0.03	95.00	100.00	Pass
JPCP transverse cracking (percent slabs)	15.00	8.56	95.00	99.87	Pass

Figure 64. AASHTOWare Pavement ME Design Distress Prediction Summary for 7 in. Overlay, and 13 ft Widen Slab and Asphalt Shoulders.

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	128.02	95.00	99.91	Pass
Mean joint faulting (in.)	0.12	0.06	95.00	99.99	Pass
JPCP transverse cracking (percent slabs)	15.00	11.93	95.00	98.54	Pass

Figure 65. AASHTOWare Pavement ME Design Distress Prediction Summary for 12 ft Joint Spacing and Asphalt Shoulders.

Table 20. Summary of Results.

Method	Scenario	Thickness(in.)
1993 AASHTO Guide	Original scenario	9.5
	Changing design load transfer (from tied concrete shoulders to asphalt shoulders)	10.5
	Changing concrete modulus of rupture (from 650 to 700 psi)	9.0
AASHTO Pavement ME Design Guide Improvements in Position Accuracy (vertical)	Original scenario	8.5
	Changing load transfer and edge support (from tied concrete shoulders to widened slab and asphalt shoulders)	7.0
	Changing joint spacing and load transfer (from tied concrete shoulders and 15 ft joints, to asphalt shoulders and 12 ft joints)	7.5

conducting mix designs and assembling surface preparation specifications.

6. Conclusions

This guide was developed to identify the most current procedures for designing concrete overlays. An overview of the 1993 AASHTO Guide and AASHTO Pavement ME Design Guide procedures, the more sensitive variables, and several examples were presented for

- Bonded overlays of concrete pavements,
- Unbonded overlays of concrete pavements and composite pavements, and
- Unbonded overlays of asphalt pavements.

In addition, an overview of the ACPA BCOA design methodology was presented for

- Bonded overlays of asphalt pavements and
- Bonded overlays of composite pavements.

A number of additional design procedures are available for the different types of concrete overlays that are not discussed in this guide. It is important for the pavement designer to recognize the requirements, the most relevant design variables, and the strengths and weaknesses of any design procedure. The intent of this guide is to assist in that task.

Furthermore, it is important to recognize that effective concrete overlay implementation involves other factors equally important to design, such as existing pavement evaluation, mixture design, surface preparation, and construction.

Finally, it should be recognized that there is a significant amount of ongoing research and development in the area of concrete overlay design. For example, an overview has been presented of ongoing Pooled Fund Study TPF-5(165), Development of Design Guide for Thin and Ultrathin Concrete Overlays of Existing Asphalt Pavements, which is being conducted to develop a new design guide and software for bonded concrete overlays of existing asphalt pavements. In addition, as previously mentioned, several State highway agencies are currently evaluating, calibrating, and working to implement the AASHTO Pavement ME Design Guide and its corresponding software.

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