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Development of an Improved Design Procedure for Jointed Unbonded Concrete Overlays on Concrete or Composite Pavements

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PROJECT TITLE

Development of an Improved Design Procedure for Jointed Unbonded Concrete Overlays on Concrete or Composite Pavements

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Introduction

An unbonded concrete overlay (UBOL) is a type of rehabilitation method in which the new overlay is isolated from an existing concrete or composite pavement using a separator layer (Smith, Yu, and Peshkin 2002). The separator layer, commonly referred to as an interlayer, historically has consisted of a thin (1 in. to 2 in. thick) hot-mix asphalt (HMA) material.

Recently, non-woven geotextile fabrics have also become a popular interlayer option for UBOLs on concrete. By providing a shear plane for differential movement, the separator layer prevents the formation of reflective cracking and serves as a de-bonding layer between the two concrete layers (Torres, Rasmussen, and Harrington 2012).

The interlayer also provides a level surface for the overlay and isolates the overlay from the underlying distresses and irregularities (Smith, Yu, and Peshkin 2002). As a result, the interlayer and existing pavement serve as a stable foundation for a concrete overlay. For a composite pavement, the existing asphalt is sometimes milled to 3 in. or less so that it can serve as the interlayer.

Figure 1 illustrates a typical cross-section of a jointed UBOL placed on an existing concrete pavement.

Background

UBOLs have been used since 1916 as a successful method of rehabilitation. Still, there is a need for a design procedure that can account for the performance of the interlayer and for guidance on the design and construction features that can make UBOLs a more cost-effective solution. Even though there are many U.S. highway agencies that have routinely used this type of overlay, there are other agencies that do not even consider rehabilitation with UBOLs, citing the lack of familiarity and clear guidance.

In addition, recent design analysis and rehabilitation of concrete pavement innovations in UBOL technology have led to the introduction of new types of interlayers, such as non-woven geotextiles, as well as the design of UBOLs with panel sizes as small as 6 ft by 6 ft. The effect of these newer design features on the performance of UBOLs could not previously be accounted for when establishing the thickness of UBOLs.

The purpose of this MAP Brief is to summarize the advancements in UBOL design procedures coming from the recently completed transportation pooled fund TPF-5(269) study, which was led by the Minnesota Department of Transportation, with support from seven other states including Georgia, Iowa, Kansas, Michigan, Missouri, North Carolina, and Oklahoma.

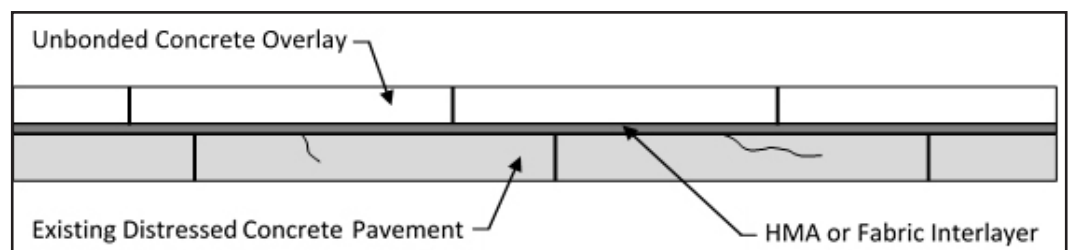


Figure 1. Typical UBOL on existing concrete pavement

Pooled-Fund Study

The goal of this eight-state pooled-fund study was to develop a stand-alone national design procedure that would result in improved performance and lifespan prediction of jointed UBOLs constructed over existing concrete or composite pavements. The new procedure incorporates the best features from previous UBOL design procedures, with new structural models that consider the effects from the environment and the behavior of the wide range of panel sizes and interlayer systems currently in use.

To achieve the goal, the research team

1. reviewed literature pertaining to the design and performance of UBOLs and performed site visits to investigate failure modes,
2. performed a laboratory investigation to characterize the response and performance of interlayers, and
3. developed improved mechanistic-empirical cracking and faulting models for jointed UBOLs.

Literature Review and Field Investigations

Existing design procedures

A review of literature related to design procedures for UBOLs revealed six relevant methods. These procedures were as follows:

- Corps of Engineers (Departs. of Army and Air Force 1979; Army Corps of Engineers 2001)
- AASHTO (1993)
- Portland Cement Association (PCA) (Tayabji and Okamoto 1985)
- Minnesota DOT (1993)
- FAA (Rollings 1988)
- Pavement M-E (NCHRP 2004)

Examining these procedures, the following 13 design considerations were reviewed:

- Analytical model
- Failure criteria
- Interface characterization
- Material properties
- Difference in strength/modulus of overlay and base pavement concrete
- Distress in existing pavement prior to overlay
- Fatigue effects of traffic on uncracked existing pavement
- Development of cracking in existing pavement after overlay
- Temperature curling and moisture warping

- Joint spacing
- Joint load transfer
- Drainage
- Interlayer

Many of these procedures account for these factors in an inconsistent manner, while others do not consider them at all (Khazanovich et al. 2020). This inconsistency clearly confirmed the need to develop an improved rational design procedure for UBOLs.

Historical performance of UBOLs

In addition to six specific UBOL performance studies highlighted in the report, the research team also collected information on the design and performance of UBOLs in several states participating in the pooled-fund study. Highlights from that effort are provided below.

Minnesota Department of Transportation

The Minnesota Department of Transportation (MnDOT) has constructed many UBOL projects over the last several decades. MnDOT also has a comprehensive database of UBOL condition information collected over their service lives.

Relevant data were available for 608 sections, representing a total of 6327 records taken over the service lives of all sections. With project ages ranging from one to 26 years, there were a wide variety of pavement conditions to examine. MnDOT has used several design procedures including a MnDOT-modified AASHTO 1981, Corps of Engineers, and a MEPDG-based procedure named MnPAVE Rigid.

Michigan Department of Transportation

The Michigan Department of Transportation (MDOT) provided data on almost 30 UBOLs constructed between 1984 and 2013. These overlays were designed using the AASHTO-93 design procedure, which is the same procedure used to design standard concrete pavements on grade in Michigan.

Overlays in Michigan are typically 6–8 in., though more recently some 4-in. thick overlays have been constructed. Dense-graded HMA was used as the interlayer material until 2003, when they started using a more open-graded HMA to construct the interlayer. This change was made to reduce pumping and erosion of the interlayer.

Missouri Department of Transportation

The Missouri Department of Transportation provided data on 10 overlays ranging in age from one to 22 years. The AASHTO-86 and AAHSTO-93 methods were used to design most of the older overlays, while the ACPA design method was used for overlays built in the last 5 years. Typical overlay thicknesses range from 8 in. for overlays built more than

5 years ago, to 5 in. for overlays designed using the ACPA design method.

The older, thicker overlays had a joint spacing of 15 ft, while the newer, thinner overlays use a panel size of 6 ft by 6 ft. Most of the 8-in. thick overlays featured 1.25-in. dowels, while 5-in. thick overlays were undoweled. Missouri was the first state in the U.S. known to use non-woven geotextile fabric as an interlayer (on Route D in 2008).

Iowa Department of Transportation

The Iowa Department of Transportation provided detailed information on UBOL pavements in the state roadway system, while noting that there also exist many overlays in the county system. These sections utilized the PCA design method, although it was noted that Iowa is working toward implementing Pavement M-E for designing UBOL. The UBOL design has been modified locally by including rebar in the longitudinal joint at the pavement edge when widening existing pavement. Many of the performance trends observed by Iowa pavement engineers were affected by lane widening included in the UBOL construction.

LTPP database

The performance of UBOLs included in the LTPP database was also examined extensively. Many of these overlays included interlayer materials not currently used, such as chip seals. This data was very informative and helpful in establishing failure modes commonly exhibited by UBOLs.

General observations and guidelines

Based on site visits and the design and performance data obtained from many state, national, and local agencies, the following observations and guidelines unique to UBOLs were identified:

- HMA interlayers can exhibit pumping and erosion (see resulting longitudinal cracking in Figure 2).
- Cracking and spalling can often be traced to dowel bar misalignment (due to difficulty in dowel basket anchorage).



Figure 2. Longitudinal cracking attributed to erosion of interlayer

- Reflective cracking is rare, but has been observed in concrete overlays as soon as 5 years after paving when the existing pavement is not fully supported.
- Clear drainage paths must be designed and maintained for good performance.
- Crown corrections to encourage drainage should be made in the concrete overlay and not in the interlayer. The depth of the saw cut may need adjustments through thicker areas of pavement.
- Pre-overlay repairs were deemed to be necessary only for severely distressed areas where support conditions are not stable or uniform.
- UBOLs have exhibited longitudinal cracking if panels are too wide for their thickness, or are placed over a narrower concrete or composite pavement that provides differential support conditions.
- Dowel bars improve performance in thicker overlays.
- A knife-edge technique can be used successfully to create longitudinal joints for “big block” (6 feet by 6 feet panel) pavements.
- The only reported distress in UBOLs with a fabric interlayer occurred in an area where the fabric was transitioned into an asphalt interlayer.

Laboratory Study

Interlayer characterization

In this study, a laboratory investigation was employed to examine the effects of an interlayer on the response of a concrete overlay structure under load. To accomplish this, 6-in. wide overlay specimens (see Figure 3) were tested to evaluate four different mechanisms:

- deflection characteristics of the interlayer,
- friction developed along the interface between the interlayer and the overlay,
- ability of the interlayer to prevent reflective cracking, and
- bond strength at the interface of the interlayer.

Both HMA and nonwoven geotextile fabric interlayer systems were considered. The objective of this investigation was

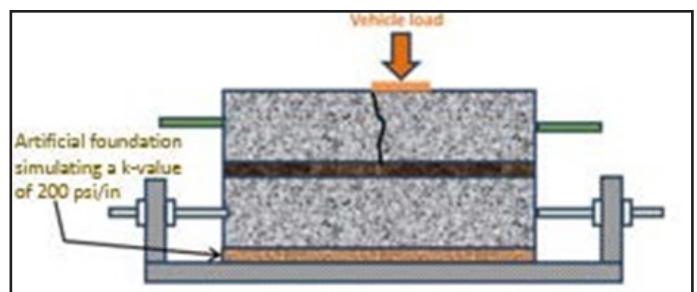


Figure 3. Depiction of laboratory beam test to characterize interlayer mechanisms

to establish parameters for each interlayer system that could be used to develop structural models, which in turn could be used to develop a mechanistic-empirical design procedure for UBOLs.

Results from the laboratory testing served as inputs to a Totski model (Totski 1981; Khazanovich 1994; Khazanovich and Ioannides 1994), which was chosen as the structural interlayer model for the new design procedure. This model, shown in Figure 4, simulates an overlay and a slab resting on a spring interlayer supported by a slab resting on a Winkler model spring foundation. The advantage of this model is that it is capable of explicitly modeling the “cushioning” property of the interlayer.

Overlay Structural Modeling

Development of new cracking models

Cracking is an important deterioration mechanism of UBOLs because it represents one of the principal modes of structural deterioration for jointed concrete pavements. In the past, various models were proposed for predicting cracking in UBOLs. The AASHTO Pavement M-E cracking model is the most advanced and sophisticated model available today. Nevertheless, that model has limitations that needed to be addressed, specifically for thinner UBOLs with smaller panel sizes. The AASHTO Pavement M-E procedure is only applicable for unbonded overlays with thickness, slab width, and slab length greater than 6 in., 12 ft, and 10 ft, respectively.

One of principal limitations of the Pavement M-E cracking model is that the primary failure mode is mid-panel transverse cracking of panels. Observed field performance has shown that, while this may be appropriate for thicker UBOLs, thinner UBOLs exhibit primarily longitudinal cracking in the outer wheel path. To address this, a new longitudinal cracking model was developed.

Similar to the Pavement M-E cracking model, the newly developed cracking model utilized the incremental damage approach and Miner’s linear damage accumulation hypothesis. While the Pavement M-E cracking model computes damages at two locations, the new model does so at four locations:

- the top and bottom of the overlay adjacent to the lane/shoulder edge at mid-slab and
- the top and bottom of the overlay adjacent to the transverse joint in the outer wheel path.

Another limitation of the Pavement M-E procedure is its inability to adequately model interaction between the PCC slab and the underlying layer. The Pavement M-E analysis assumes that the unbonded overlay and the existing pavement have the same deflection profiles. The structural contribution of the interlayer is ignored. In reality, an interlayer may provide some “cushioning” to the overlay. The ISLAB2005 Totski model permits direct accounting of this effect.

The developed ISLAB2005 model accounts for the effect of numerous factors on the magnitude of bending stresses in unbonded overlay slabs, some of which include the following:

- Overlay and existing concrete slab thicknesses, modulus of elasticity and coefficient of thermal expansion
- Interlayer and subgrade stiffness
- Joint spacing
- Temperature distribution throughout the slab depth
- Load configuration and axle weights
- Dowel bar stiffness and restraint

To avoid direct inclusion of a proprietary finite element analysis program into the new UBOL procedure, and to improve computation efficiency of the design program, rapid solutions (neural networks) were developed for determining the critical stresses required for computing each type of fatigue damage. Critical stresses were determined for factorials of ISLAB2005 runs of over 20 factors for the same crack locations listed above.

In addition to modifications to the Pavement M-E cracking models, there needed to be major modifications made to the processing of EICM (Enhanced Integrated Climatic Model) temperature data for the modified UBOL cracking model. Thermal gradients in UBOLs greatly affect the critical stresses that contribute to cracking. Distributions of thermal gradients are required over each month throughout the year (both day and night). The EICM module of Pavement M-E generates the thermal profiles throughout concrete slab thickness for every hour of pavement life.

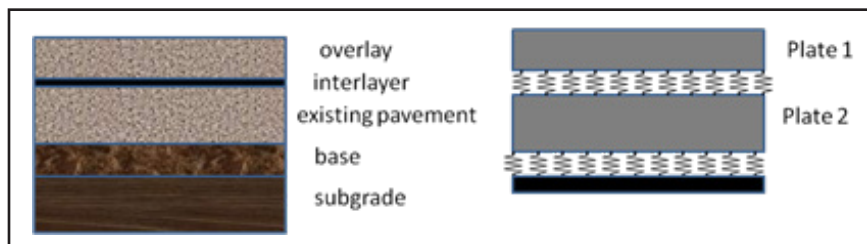


Figure 4. UBOL system (at left) and Totski model for layer interface

To improve computation efficiency, the Pavement M-E procedure converts those hourly predictions into monthly distributions of probability of combinations of traffic and temperature (known as the thermal linearization process). In this study, an alternative approach was developed using adaptations of approaches proposed by Hiller and Roesler (2010) and Khazanovich and Tompkins (2017), involving the following steps:

1. EICM analysis is conducted to predict hourly distributions of the temperature throughout the UBOL pavement system.
2. Each hourly temperature profile is approximated by a quadratic temperature distribution.
3. The frequency distribution of linear and quadratic coefficients is created.

Following this, a built-in curl analysis was carried out for UBOLs. A recently completed NCHRP 1-51 study (Khanzovich and Tompkins 2017) suggested that built-in curl characterization for pavement performance models should not be limited to a single parameter/value. That study proposed to modify the built-in curl factor in pavement performance modeling by dividing the default Pavement M-E parameter into two different built-in curl temperature gradients for daytime and nighttime conditions (ΔT_{bot} and ΔT_{top} , respectively).

Furthermore, it proposed that the developed model for built-in curl consider the properties of the concrete slabs thickness and stiffness of the slab and base layers; this model thus ensures that projects with stiffer bases will have more exaggerated levels of built-in curl. The existing pavement provides a much stiffer foundation to an unbonded overlay than a base layer provides to a new concrete pavement. Therefore, it was hypothesized that the amount of built-in curling depends on the stiffness of the overlay and the existing pavement, overlay joint spacing, and stiffness of the interlayer. A new built-in $\Delta T_{built-in}$ was proposed and implemented into the new cracking model.

The UBOL cracking prediction process developed in this study is a modification of the Pavement M-E cracking prediction process for rigid pavements. The main steps included the following:

1. Assembling design inputs for a specific site condition, such as traffic, climate, existing concrete pavement properties, and foundation and defining the interlayer and overlay properties as well as the design features such as joint spacing, dowel diameter, and shoulder type.
2. Processing inputs to obtain monthly traffic, material, and climatic inputs needed in the design evaluation for the entire design period.
3. Computing structural responses (stresses and deflections) using finite element-based rapid-solution models for each axle type and load, as well as for each damage-calculation increment throughout the design period.
4. Calculating accumulated top surface and bottom surface damages at the lane-shoulder joint and the transverse joint for each month of the entire design period.
5. Predicting cracking at the end of the entire design period.

The transverse cracking model was calibrated using the LTPP projects in the Pavement M-E calibration database (Sachs, Vandebossche, and Snyder 2014). Figure 5 presents a comparison of the calibrated cracking model predictions with the measured cracking. It can be observed that the model shows a good fit of the field data and does not exhibit a bias in predictions.

This was followed up by a reliability and as-built variation analysis. Analysis of the sensitivity plots suggested that the exhibited predictions had reasonable trends. The only exception is the reduction of the required overlay thickness for heavy volume traffic if a fabric interlayer is used instead of an HMA interlayer. Due to lack of long-term performance data for unbonded overlays with fabric interlayer under heavy traffic (the first U.S. application of fabric interlayers was in 2008), this trend cannot be confirmed or disproved.

Development of new faulting model

While the development of faulting of transverse joints is largely mitigated by dowel bars in thicker UBOLs, the use of thinner undoweled UBOLs has demonstrated that this distress can occur under certain circumstances. Only more recent design procedures are capable of factoring in joint faulting, and the basis for their models was that of slabs on unbound bases. This project reviewed existing faulting models and developed a rational approach specifically for UBOLs.

Six previously developed transverse faulting models were reviewed:

- ACPA
- SHRP P-020
- FHWA RPPR 1997
- LTPP Data Analysis Study
- NCHRP 1-34
- AASHTO Pavement M-E

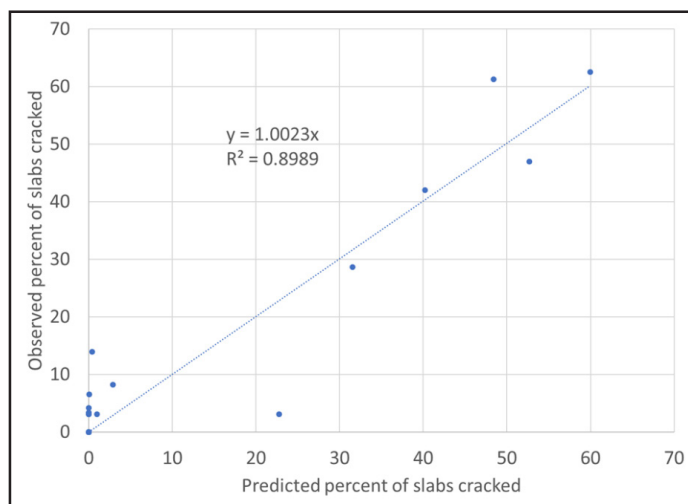


Figure 5. UBOL cracking model predictions compared to LTPP observations

Of these procedures, important predictive parameters included the following: the differential energy between the loaded and unloaded slabs, an indication of the amount of precipitation, an estimate of the traffic, the presence of dowel bars, and an indication of the erodibility of the base material. The Pavement M-E faulting model was the standard mechanistic-empirical framework currently available. Therefore, the framework for the UBOL faulting model developed in this project adopted a similar approach to calculate UBOL joint faulting.

To predict joint faulting, the UBOL pavement deflection basins were obtained from structural modeling. Incremental faulting calculations require many time-consuming finite element runs, so neural networks were adopted. A range of parameters and critical responses were developed to generate a factorial of finite element runs for use in developing the faulting model. ISLAB2005 was chosen as the modeling software for UBOL joint faulting. Models were created for both asphalt and fabric interlayers.

The effects of temperature gradients are also considered in the analysis. It was established that there was no significant relationship between interlayer temperature and the resulting Totsky K-value for either the asphalt or fabric interlayers. Therefore, there was not a need to account for the temperature of the interlayer when defining the stiffness of the interlayer (Totsky-K).

A serious limitation to previous UBOL design procedures is that they do not directly account for the fact that pumping occurs in the interlayer when faulting develops in UBOL. This newly developed fault prediction model better captures the effects of the interlayer on the development of faulting by incorporating the erodibility of the interlayer into the faulting model. Also, a newly developed erosion model was added so that material properties, such as percent binder, air void content and percent fines, could be accounted for when establishing the erodibility of the interlayer.

Direct inputs for predicting joint faulting include the one-way average daily traffic, percent of trucks, the number of lanes in each direction, the growth type, and the growth rate. With the equivalent temperature gradients defined for each calibration section, the iterative faulting calculations are then performed. The primary calculation for each month determines the differential energy. The effects of aggregate interlock on joint stiffness are also considered. The non-dimensional aggregate joint stiffness values are calculated for each month in a manner similar to that in Pavement M-E.

The calibration database used to calibrate the UBOL faulting model consists of 26 different

sections from eight different states in the U.S. The calibration sections are comprised of six LTPP sections, six sections from the MnROAD facility, and 14 Michigan DOT pavement sections. Of the sections, nine are undoweled, while the rest are doweled. The age of the sections ranges from approximately 2.5 to 26.5 years, with an average of age of 10.5 years. In terms of ESALs, the traffic ranges from approximately 0.99 million to 24.5 million, with an average value of around 8 million ESALs. The predicted versus measured transverse joint faulting is presented in Figure 6.

New UBOL Design Procedure

After six years of development, this pooled fund study produced a new UBOL design procedure named “UBOLDesign.” This standalone software can perform two types of analyses—performance prediction and design reliability. If the performance prediction option is selected, the program predicts the percentage of cracked slabs and mean joint faulting at the end of the design life for a given overlay thickness. If the reliability analysis option is selected, then the program finds the overlay thickness meeting the specified cracking reliability level and predicted joint faulting for the specified faulting reliability level.

Using the graphical user interface of the software package, the user can provide the following information:

- Climate: choose from 68 locations throughout the U.S.
- Traffic volume: expressed in heavy commercial two-way annual daily trucks, number of lanes, and linear yearly growth rate
- Overlay slab size: 6 ft by 6 ft or slab width of 12 ft with joint spacings between 12 and 16 ft
- Shoulder type: HMA or tied PCC
- Concrete strength
- Existing pavement thickness and stiffness
- Interlayer type

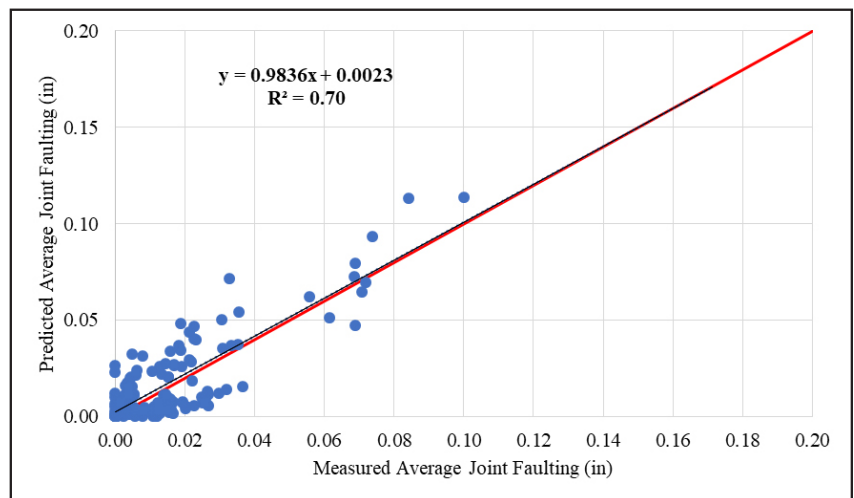


Figure 6. Measured vs. predicted UBOL transverse joint faulting

- Mix design if an HMA interlayer is used:
 - Effective binder content by volume
 - Percent passing #200 sieve
 - Percent of air voids

The following ranges of the input values can be analyzed by the current version of the program:

- Reliability level: 40%–99%
- Overlay thickness: from 6–12 in. for conventional (12 ft) width overlays and 4–10 in. for short slabs (6 ft by 6 ft)
- Design life: from 1–100 years
- Two-way annual average daily truck traffic (AADTT): from 0–10,000
- Existing PCC thickness: from 6–16 in.
- Existing PCC elastic modulus: from 500,000–10,000,000 psi

Figure 7 depicts the main input screen for a reliability analysis design. This new procedure has been validated for a wide range of climates and traffic, producing what are believed to be more rational overlay designs.

Project Suitability and Interlayer Guidance

An important part of any pavement rehabilitation project is the suitability of various design options. One task in this study outlined the factors determining suitability of an existing concrete or composite pavement to serve as a platform for an UBOL. The resource cited as most helpful in these decisions was identified as concrete overlay guidelines published by the CPTECH Center at Iowa State University (Harrington and Fick 2014).

A primary focus of this project was to substantially improve the understanding of the behavior and role of the interlayer

in an unbonded concrete overlay system. This included providing detailed guidance on selecting the most suitable type of interlayer for a project, given the design of the overlay and condition of the existing concrete or composite pavement.

Summary

Following a six-year, eight-state pooled-fund study effort, there now exists a new mechanistic-empirical procedure for the design of jointed unbonded concrete overlays placed on existing concrete or composite pavements. The procedure, named “UBOLDesign,” accommodates many more design inputs than previously available procedures. The study also produced guidance on project selection, and made significant advancements in understanding the behavior and selection of suitable interlayers. As a result of this effort, UBOLs may now be more efficiently designed and provide enhanced performance.

A draft version of the executable web-based software can be found at <https://uboldesign3.azurewebsites.net/>.

The final project report is available at <http://www.dot.state.mn.us/research/reports/2020/202008.pdf>.

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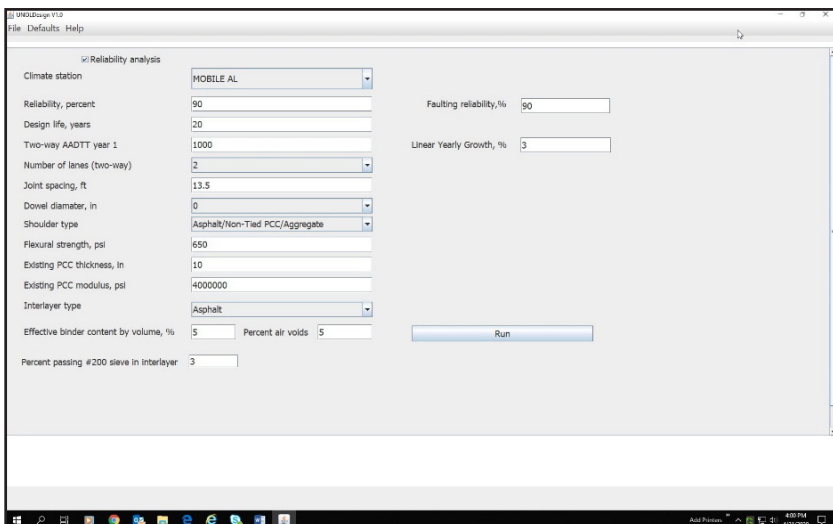


Figure 7. Main input screen (for reliability option)

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